MASTER'S THESIS

Modelling Future Pathways on Carbon Sequestration by Nut Orchards in the Temperate Climate of the Netherlands

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Thesis MSc Environmental Sciences (NM990A)
Faculty of Science (Environmental Sciences Dept), Open Universiteit

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Scenario's voor de vastlegging van koolstof in notenboomgaarden in het gematigde klimaat van Nederland

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Source image at the title page: Nut orchard 't Joostenhuus, Breedenbroek NL (Erik Roest).

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Colophon

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Area of study was the nut orchard ‘t Joostenhuus, of Harm and Rieky Tuenter at Breedenbroek.

Preface

This thesis report is the final part of my master study Environmental Sciences at the Open University of the Netherlands. The master Environmental Sciences at the Open University gives students a lot of opportunities to compile a study program fitting their needs and interests. I seized this opportunity by structuring many of my assignments around the knowledge triangle of forests, nature and climate. Reports that I wrote were about Globally applicable sustainability criteria for afforestation, Sustainable forestry policy of the European Union, Nitrogen problems in the Netherlands and Climate change (with an emphasis on the fresh water system). This thesis report also fits well into this triangle, because it is structured around the interface of the greenhouse gas carbon dioxide, trees and soil.

Many people have contributed to this study. My special gratitude goes to the owners of the nut orchard ‘t Joostenhuus in Breedenbroek, Harm and Rieky Tuenter, for all their help and hospitality and to Ton Baltissen for his inspiring help and for initiating the design of this research. I also want to thank my thesis supervisors: Angelique Lansu (Open University) and Stefan Dekker (Utrecht University).

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Erik Roest

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Abstract

Planting trees is suggested as a measure to sequester carbon (C), but might conflict with agricultural land use. C-sequestration can act as a climate engineering measure to mitigate increasing CO_2 emissions to the atmosphere. Changing grass- and cropland into nut orchards might increase C-sequestration, without encroaching on agricultural land use. Nut orchards can easily be transformed into an agroforestry system by combining nut production with another agricultural activity. Data on the impact of land use change from agriculture to agroforestry systems based on nut orchards in the temperate zone are scarce.

C-sequestration dynamics in soil organic carbon (SOC) and in the above- and belowground biomass of trees and grasses in nut orchards have been analyzed. The object of study were nut orchards, aged between 8 and 124 years old, located on a sandy soil in the temperate zone of the Netherlands. Field measurements on trees and lab results on soil data from chronosequences from grass- and cropland to stands of *Corylus avellana* (Hazelnut) and *Juglans regia* (Walnut) trees were combined with modelling future pathways of C-sequestration at the level of parcels. All results pertain the top 60 cm of the soil and include carbon stored in harvested wood. Data on belowground biomass of grasses and trees were based on allometric equations.

Total C-sequestration ranges from 0.8 to 3.4 Mg C ha^{-1} yr^{-1} (mean 1.72 Mg C ha^{-1} yr^{-1}). Compared to control parcels, C-sequestration in SOC ranges from -/-0.1 to 2.2 Mg C ha^{-1} yr^{-1}, in aboveground biomass from 0.3 to 1.2 Mg C ha^{-1} yr^{-1} and in belowground biomass from 0.02 to 0.4 Mg C ha^{-1} yr^{-1}. Overall, these results confirm the C-sequestration potential of changing grass- and cropland into nut orchards in the temperate zone to mitigate global CO_2 emissions.

Samenvatting

Het planten van bomen wordt vaak genoemd als maatregel om koolstof(dioxide) vast te leggen, maar dit gaat vaak ten koste van het agrarisch productieareaal. Het vastleggen van koolstof kan het klimaat beïnvloeden en op die manier de toegenomen CO_2 emissies compenseren. Door grasland en bouwland om te zetten in notenboomgaarden kan meer CO_2 worden vastgelegd, zonder dat de voedselproductie verminderd. Een notenboomgaard is niet hetzelfde als een agrobosbouw, maar met een kleine aanpassing kan het dat wel makkelijk worden. Er is echter nog weinig onderzoek gedaan naar de omzetting van landbouwgrond in agrobosbouw.

Dit onderzoek doet verslag van de dynamiek van koolstofvastlegging in de bodemorganische stof en in de boven- en ondergrondse biomassa van bomen en grassen in notenboomgaarden. De onderzochte notenbomen waren tussen de 8 en 124 jaar oud en staan op een zandige bodem in het gematigde klimaat van Nederland. In het onderzoek zijn veldmetingen aan bomen uitgevoerd en bodemmonsters genomen in chronosequenties van gras-, respectievelijk bouwland naar notenboomgaarden van *Corylus avellana* (hazelnoot), respectievelijk *Juglans regia* (walnoot). Dit is gecombineerd met het modelleren van scenario's voor de vastlegging van koolstof. Alle resultaten hebben betrekking op de bovenste 60 cm van de grond en zijn inclusief geoogst hout. Het volume van de ondergrondse biomassa is bepaald met behulp van allometrische vergelijkingen.

De totale koolstofvastlegging bedraagt 0,8 á 3,4 Mg C ha^{-1} yr^{-1} (gem. 1,72 Mg C ha^{-1} yr^{-1}). De koolstofvastlegging ten opzichte van de controlepercelen in de bodemorganische stof bedraagt -/-0,1 á 2,2 Mg C ha^{-1} yr^{-1}, in bovengrondse biomassa 0,3 á 1,2 Mg C ha^{-1} yr^{-1} en in ondergrondse biomassa 0,02 á 0,4 Mg C ha^{-1} yr^{-1}. Deze resultaten bevestigen de kansen voor het mitigeren van CO_2-uitstoot door het vastleggen van koolstof door de omzetting van gras- en bouwland in notenboomgaarden in een gematigd klimaat.

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1 Introduction

Carbon sequestration by agroforestry as a climate engineering measure is promising to contribute to the goals of the Paris agreement to lower Carbon dioxide (CO_2) in the atmosphere. Data on the impact of land use change (LUC) on carbon sequestration -from agricultural land use to agroforestry- are promising but scarce. This study is aimed to model – at the level of parcels - future pathways of carbon (C) sequestration as a result of this LUC. Data were collected from chronosequences of nut orchards on sandy soils in the temperate climate of the Netherlands (Breedenbroek, Gelderland).

The Paris Agreement was signed by many governments to limit global warming by restricting CO_2-emissions and stimulating carbon sequestration (Rogelj et al., 2016). The world is facing large risks of climate change (Oppenheimer et al., 2014) which is very likely being caused by emissions of greenhouse gases with an anthropogenic origin (Stocker et al., 2013). CO_2 is the most emitted greenhouse gas (GHG). CO_2 is produced during e.g. the combustion of fossil fuels, high yield agricultural production and LUC, e.g. deforestation. Stocker et al. (2013) describe that rising atmospheric CO_2-levels lead to increased radiative forcing, which results in higher temperatures, climate change and negative side effects like the ones described by Oppenheimer et al. (2014).

Carbon can be found in all parts of the earth and its atmosphere. The main reservoirs (stocks) of C that are frequently altered are the atmospheric C-stock (Figure 1), mainly present as CO_2, Ocean C-stock (Ocean), soil C-stock to a depth of 1 m (Soil) and vegetation C stock (Veg.). Carbon runs from one to another C-stock in all kinds of directions, in all kinds of chemical compounds; e.g. as CO_2 in the air. The ocean contains the most C (38,000 Pg), and the atmosphere contains the least (67 Pg). Between these stocks there are fluxes, which at present cause a general increase of atmospheric C and a decrease of soil and vegetation C-stocks. This general increase is mainly caused by anthropogenic C-release (10.7 Pg) e.g. combustion of fossil fuel, which originates from the soil too, but from larger depth than one meter, LUC and cement production. Minasny et al. (2017) label C-sequestration in the soil as an important means to help mitigate GHG emissions and Boysen et al. (2017) also label C-sequestration in vegetation as a significant means, therefore this study will concentrate on biochemical fluxes of C to soil and vegetation.

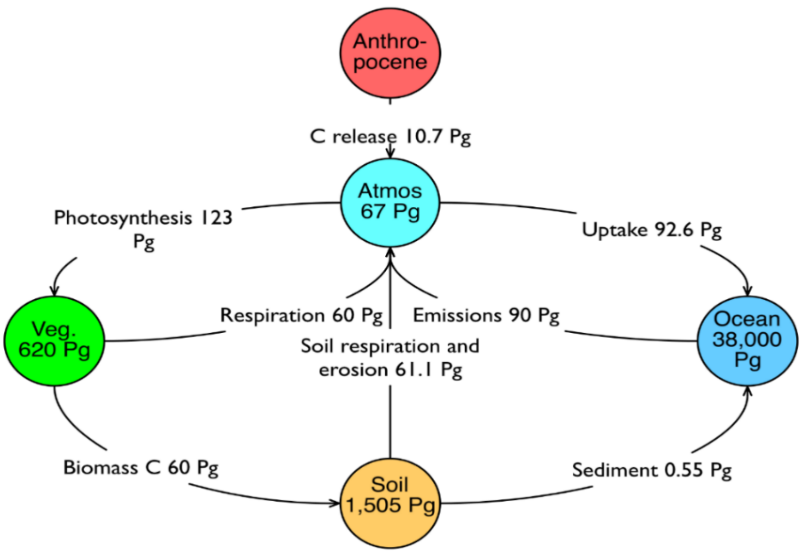

Figure 1 Global carbon and fluxes between the major earth's systems (in Pg C). Redrawn from Lal (2018) which was redrawn from data in Batjes (1996, 2016); Lal (2004) and Le Quéré et al (2017).

Lal (2018) uses the term terrestrial ecosystem carbon, as the sum of vegetation C-stock and soil C-stock (Figure 2). These terrestrial C-stocks add CO_2 to the atmosphere, and are strongly influenced by high yield agricultural production and LUC. Lal (2018) writes that on a global scale approximately 190 ± 65 Pg C has been released between 1750 and 2015 from the soil as a result of LUC and C is still being lost at a rate of $1.3 \pm 0.7\ Pg \cdot yr^{-1}$. Within soil carbon, Wotherspoon, Thevathasan, Gordon, and Voroney (2014) distinguish three groups: soil organic carbon (SOC), belowground biomass (BGB) and soil inorganic carbon (SIC). In this report we used the words belowground biomass (BGB) and aboveground biomass (AGB), instead of vegetation C-stock, to make a distinction between AGB and BGB. For vegetation C-stock, the sum of BGB and AGB, we used the term biomass C-stock. Berge, Schroder, Olesen, and Giraldez Cervera (2017) and Nair (2012) describe that soil organic carbon (SOC), is important for soil fertility, soil structure and hydraulic qualities. Subsequently it affects biodiversity, water quality, air quality and soil productivity, and so food supply and agricultural income. This means that rising atmospheric CO_2-levels and decreasing SOC are interconnected problems.

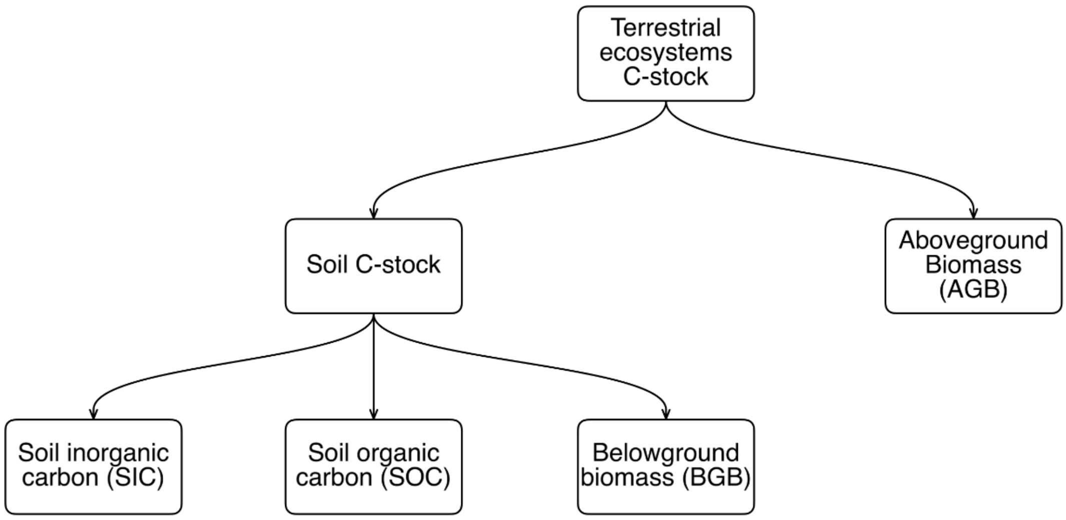

Figure 2 Different types of soil C stock (Aboveground Biomass = AGB). Based on the diagram of Lal (2005).

1.1 Problem definition

How can atmospheric CO_2-levels be reduced and soil C-stock improved? The DPSIR model of Smeets and Weterings (1999) can help to analyse and visualise this problem, by focusing on the driver, pressure, state, impact and responses. A schematic display of the previously outlined problem shows that the problem originates in driving forces, e.g. the need for heating and food, that lead to certain pressures on the environment, e.g. high yield agricultural production and LUC (Figure 3). These pressures lead to an altered state of the environment, e.g. increased CO_2-levels, which subsequently have an impact, like climate change. These impacts stress mankind to respond to the problem.

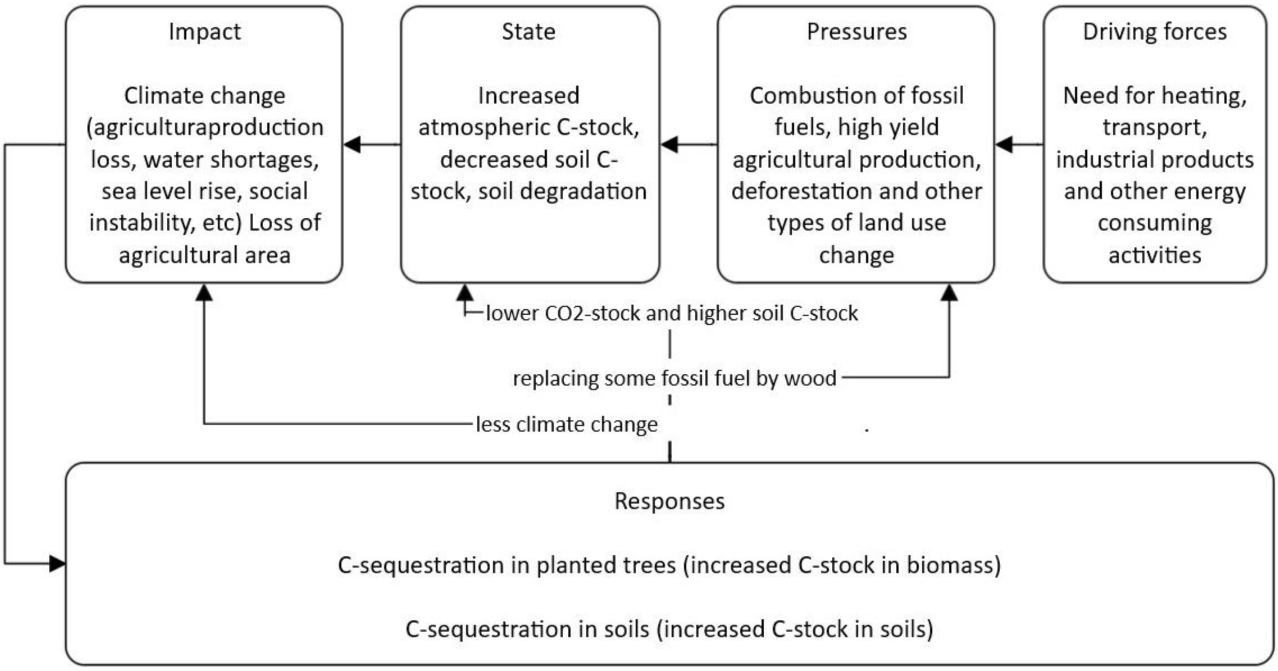

Figure 3 Carbon sequestration as a response to rising CO2-levels described by the DIPSR-model of Smeets and Weterings (1999)

Science and governments have been studying and discussing the relation between CO_2 and climate change for decades, which has led to the Paris agreement (Rogelj et al., 2016). Governments that signed the Paris agreement are committed to limit CO_2-emissions and to stimulate C-sequestration. C-sequestration, as a means to mitigate CO_2-emissions can be done by storing CO_2 in emptied natural gas fields or by artificial stimulation of C-sequestration by oceans, which e.g. Rogelj et al. (2016) calls carbon capture and geological storage (CCS). More natural ways of C-sequestration are good soil management and the planting of trees, which store C in their wood (biomass C stock). Edenhofer et al. (2014) describe 'Agriculture, Forestry and Other Land Use' as one of the sectors that can take mitigation measures for CO_2-emissions. This is a kind of C-sequestration, which Heck, Gerten, Lucht, and Boysen (2016) call terrestrial carbon dioxide removal (tCDR).

IPCC (2014) mentions afforestation as part of the mitigation scenarios and points out that the sector of agriculture, forestry and LUC as a whole is responsible for a quarter of net anthropogenic GHG emissions. Since anthropogenic GHG emissions by forestry and LUC (e.g. deforestation) are so large, this study focused on the possibilities of tCDR in the form of C-sequestration by soils, afforestation (the opposite of deforestation) and LUC (from agricultural land to agroforestry). The next sections successively elaborate the literature on C-sequestration by good soil management, afforestation and agroforestry.

1.1.1 Soil

The idea of a global research programme on capturing C in the soil was initiated in 2015 during the Convention on Climate Change in Paris (Minasny et al., 2017). The intention of this research programme, called 'quatre-promille' or 4 per 1000, is to mitigate CO_2 emissions by increasing SOC with 0,4% per year. A global increase of SOC not only helps to lower atmospheric CO_2-levels and the risk of climate change, but also improves soil quality. From a sequestration point of view passive carbon is preferred above active (labile) carbon, because passive carbon is very stable, unlike active carbon which is quickly available for plants and more vulnerable to decomposition which will transport carbon back to the air (SoilWealth, 2018). Lal (2018) determines five mechanisms of importance for stabilisation of SOC: physical, chemical, microbial, biochemical and ecological (e.g. biological) mechanisms.

C-sequestration in the soil will be a temporary solution, which can buy us time, because soils under natural conditions do not have unlimited capacity to sequester carbon. Hence, many soils around the world could sequester carbon, because Lal (2018) calculated that the historic global loss of SOC by LUC and agricultural overexploitation is about 135 Pg C, so the potential for additional C sequestration in SOC is large (compared to atmospheric C of 67Pg).

The C-sequestration rate at agricultural soils ranges from 0.10 Mg ha^{-1} yr-1 to 1.0 Mg ha^{-1} yr-1, with the highest sequestration rates in cropland and the lowest in pastures (Table 1). However, research of Conijn and Lesschen (2015) shows that temperature increase will lead to lower SOM levels in the Netherlands.

Table 1 Carbon sequestration rates in Soil Organic Carbon (SOC) under conditions of agricultural use.

Study	Region (AEZ)	Land use	C sequestration rate (global pot.)	Range
Minasny et al. (2017)	Global	Agriculture	0.6 $Mg \cdot ha^{-1} \cdot yr^{-1}$ (2-3 Pg·yr-1)	SOC
Lal (2018)	Global	Cropland	0.25-1.0 Mg·ha-^{1}·yr-1 (0.2-0.9 Pg yr-1)	SOC
Lal (2018)	Global	Pasture	0.10-0.175 Mg·ha-^{1}·yr-1 (0.3-0.6 Pg yr-1)	SOC
Lal (2018)	Global	Permanent crops	0.5-1.0 Mg·ha-^{1}·yr-1 (0,1-0.2 Pg yr-1)	SOC
Lesschen et al. (2012)	Temperate	Agriculture	0.63 Mg $C \cdot ha^{-1} \cdot$yr-1	SOC

The global potential for C-sequestration in agricultural soils is estimated at 2-3 Pg yr-1 by Minasny et al. (2017) and between 0.9 and 2.0 Pg $C \cdot yr^{-1}$ by Lal (2018). The potential for C-sequestration as a result of reversed desertification and afforestation was not taken into account in these studies. Afforestation might help to capture even more carbon.

1.1.2 Afforestation

Lund (2006) define afforestation as the planting of forest on land which has not been forest for 30 years or longer. In 1995 Nilsson and Schopfhauser (1995) discovered that increasing the global amount of trees by establishing large-scale plantations and agroforestry -based on a feasible scenario- could sequester about 104 Pg C in wood and SOC over a 100-year period. Based on a potential planting area of 345 million ha (Mha), this is 3 $Mg \cdot ha^{-1} \cdot yr^{-1}$. It is not a quick fix however, since Nilsson and Schopfhauser (1995) also discovered that accumulated carbon would only be significant after about 45 years. Current calculations by Krause et al. (2017) range from 55 to 89 Pg to be sequestered globally on 363 resp. 493 Mha in (harvested) biomass and soil by afforestation in an 82-year period. Boysen et al. (2017) draw the conclusion that tCDR by afforestation and tCDR by other vegetation on a global scale, combined with CCS of these vegetational carbon, can capture up to 1,424 Pg C in biomass in an 83-year period. Nevertheless, to remove that amount of carbon would require an area of 6,899 Mha and large amounts of fertilisers, which would lead to food shortages and the conversion of all natural land into bioenergy plantations. Bastin et al. (2019) concluded that 205 Pg carbon could be stored at 900 Mha over an undefined length of time. We can derive that afforestation can help to lower atmospheric CO_2-levels, but it cannot mitigate the current annual anthropogenic carbon release of 10.7 Pg/year. Hence Boysen et al. (2017) also pointed out that because of population growth a lot of area will be needed for food production. A pathway from agriculture (grassland or cropland) to agroforestry can be considered a light version of afforestation. It is worthwhile to investigate how much C can be sequestered by agroforestry.

1.1.3 Agroforestry

Cardinael et al. (2017) define agroforestry systems as a land use management system which combines the growth of trees with harvesting crops or pastures. The definition of agroforestry systems (AFS) became commonly used at the end of the seventies by authors like Combe and Budowski (1979), although the type of management had been practised for millennia. Cardinael et al. (2017) divide AFS into two main groups: silvoarable AFS which are a mixture of growing trees above cropland, and silvopastoral AFS, which combine trees with the grazing of livestock. With AFS it might be possible to sequester C both in biomass (trees) and soil.

Lorenz and Lal (2014) describe that the C-stock per hectare under agroforestry management varies widely from 1.25 Mg C·ha^{-1} in a specific parcel in Canada to more than 300 Mg C·ha^{-1} in Brazil and estimates that about 2.2 Pg carbon has been sequestered over 50 years in biomass and soil by AFS. This number is highly dependent on the area available for AFS. Aertsens, De Nocker, and Gobin (2013) estimate the potential C-sequestration if all agricultural lands in the EU were converted into agroforestry at 1.4 Pg C yr-1. The goal of changing all agricultural lands in the EU into AFS is reasonable, because EURAF (n.d.) states that about 90% of European grassland and 99% of European cropland could have some kind of AFS practise, meaning that the potential is enormous. Global values give an impression of the global potential, but values per hectare are easier to compare among one another.

Sequestration rates per hectare
Lorenz and Lal (2014) induced that tropical AFS have higher sequestration rates than temperate AFS and that sequestration rates need additional research. Therefore, we compared findings within one specific AEZ; the temperate AEZ. Cardinael et al. (2017) found accumulation rates in France in biomass and soil of 0.69 Mg·C ha^{-1}·yr^{-1} for agroforestry (type: silvoarable) compared to conventional agricultural management (AM) (Table 2).

C-sequestration rates found in other studies regarding the temperate zone range from 0.20 to 4.0 Mg C·ha^{-1}·yr^{-1}. These results make it is reasonable to conclude that more C will be sequestered in AFS systems in the temperate AEZ of Europe, than in traditional AM systems.

Most of these studies are about silvoarable AFS. For silvopastoral AFS the amount of studies is limited, so it is difficult to make predictions for this type of AFS. AFS might be a valuable attribution to solving a part of the global risk of climate change and the problem of soil degradation by the sequestration of carbon in biomass and soil, while producing food at the same time, but uncertainties about the sequestration rates are large. These uncertainties are likely caused by the large number of variables that influence C-sequestration.

Table 2 Carbon sequestration rates in agroforestry systems in the temperate Agro Ecological Zone (AEZ).

Study	Country (AEZ)	Land use	C-sequestration rate (Mg C·ha^{-1} yr^{-1}) [depth cm]	Range
Cardinael et al. (2017)	France (temperate)	conventional AM to silvoarable/ silvoarable (e.g. based on *Juglans*)	0.24 (0.09-0.46) [0-30cm]	soil
			0.65 (0.004-1.85)	Biomass (AGB+BGB)
Dold et al. (2019)	Arkansas, USA (temperate)	silvopasture	0.20	biomass (AGB)
Hamon et al. (2009)[1] as cited in Aertsens et al. (2013)	Europe (mainly temperate)	agroforestry (e.g. based on *Juglans*)	2.75 (1.5-4.0)	soil and biomass
Palma et al. (2007)	Spain (subtropics), France (temperate), the Netherlands (temperate)	cropland to silvoarable (e.g. based on *Juglans*)	Sp 0.16 Fr 0.68 Nl 1,41	biomass (AGB+BGB)
Pardon et al. (2017)	Belgium (temperate)	cropland to silvoarable (e.g. based on *Juglans*)	0.21 [0-23cm]	SOC
Sharrow and Ismail (2004)	Oregon, USA (temperate)	pasture to silvopastoral	0.52 [0-45cm]	soil and biomass (AGB+BGB)
Thevathasan and Gordon (2004)	Southern Ontario, Canada (temperate)	cropland to silvoarable (e.g. based on *Corylus* and *Juglans*)	1.65	Biomass (AGB+BGB)
Wotherspoon et al. (2014)	Ontario, Canada (temperate)	conventional AM to silvoarable/ silvopasture (e.g. based on *Juglans*)	0.8–2.1	soil and veg.
			0.3-1.0 [0-40cm]	soil
			0.52-1.08	biomass (AGB+BGB)

Spatio-temporal variety

Wotherspoon et al. (2014), who did research on silvoarable systems in Ontario, found sequestration rates are different for various tree species. Four years later Nelissen, Coussement, Pardon, and Reubens (2018) conclude that the amount of carbon that can be sequestered depends on many parameters, e.g. tree species, planting density, tree age (vegetation characteristics) and soil management. Every form of land use, vegetation and soil types has its own capacity of capturing or releasing CO_2 and this capacity also varies over time (Lesschen et al., 2012; Paul, Polglase, Nyakuengama, & Khanna, 2002).

When looking at SOC, the first seven years after planting walnut (*Juglans*) can show a decrease in SOC, according to Lu, Meng, Zhang, Yin, and Sun (2015) under conditions of a pure *Juglans* stand without intercropping, but Pardon et al. (2017) found no decrease over a time span of 3 to 5 years after planting. Paul et al. (2002) found very different values and concluded that in the first years after afforestation or after planting on a plantation, soil C stock decreases, to return at pre-planting levels after about 30 years. In 2014 Lorenz & Lal concluded that sequestration processes of carbon in AFS were not understood well enough to advice about maximising soil C-sequestration. These findings from literature show that extrapolation of sampling results taken shortly after planting is not possible because of C stock fluctuations, though time studies often comprise a short time span. Chronosequence studies can act as an alternative to time studies. Chronosequences are series of locations, which had a comparable type of management under comparable environmental conditions, but with different ages. Literature findings confirm that further research on chronosequences and longer time–series modelling is needed to be able to determine future pathways.

[1] original source not available

Sequestration rates depend in particular on the next variables:

1. Land use (vegetation characteristics)
2. Soil type (soil quality and compound quantities)
3. AEZ

Each mixture of these variables has a unique sequestration rate (e.g. Table 1), which also changes over time. The amount of all possible combinations is large, which contributes to the fact that sequestration processes are not understood very well. Studies at a level of uniform land use and subsequent LUC – as is the parcels' level – might help to better understand the processes of biochemical flows in carbon sequestration from agriculture to agroforestry.

The research of Pardon et al. (2017) is one of the research initiatives that studied the influence of AFS on SOC for the Flemish region. The study of Pardon et al. (2017) study focussed only on the specific AFS type of tree rows next to arable AFS. A comparative study by Palma et al. (2007) took place in Spain (subtropics), France (temperate AEZ) and the Netherlands (temperate AEZ), however the amount of research on the effects of AFS, specifically under temperate circumstances is limited (Cardinael et al., 2017; Dold et al., 2019) and the plurality within AFS under various environmental conditions is large.

About 0.7% of the Netherlands is covered by AFS, while the average for Europe is 3.6%, so the AFS-area in the Netherlands is relatively low, compared to the rest of Europe (Herder et al., 2017). We expect AFS to contribute to the goals of Ministerie van Landbouw Natuur en Voedselkwaliteit (2018) to stimulate circularity in Dutch agriculture, because AFS produces its own compost and is expected to use less chemical fertilisers and to contain more organic matter (OM) and more soil biological activity. These findings confirm the existence of a knowledge gap, and justify the decision to do research on AFS in Europe and especially in the temperate AEZ of the Netherlands.

Nut plantations; a specific form of AFS

Few research on AFS has been conducted in the Netherlands. The variety among AFS is thus large, that research on AFS at the parcels level has to concentrate on a specific type of AFS.

In 2018 the area of Dutch nut plantations was limited to ca. 70 ha CBS (2018). The values as provided by FAOSTAT (2014) in Bregaglio et al. (2016) show that the global demand for hazelnut fruits (nuts) is strongly increasing, so the fundamental trend justifies investing in area growth of hazelnut (*Corylus*) and *Juglans* orchards. The potential area of nut orchards in this region from the point of view of suitable growing locations is large and Baltissen and Oosterbaan (2017) calculated that potential nut sells in The Netherlands would justify 130,000 ha of *Juglans* and chestnut (*Castanea sativa*) trees in the Netherlands (7.4% of all Dutch agricultural lands). Therefore, this research concentrated on a specific type of AFS; the growing of *Juglans* and *Corylus* trees in a nut orchard above grassland respectively cropland at one specific location in Gelderland, The Netherlands. Not all nut plantations meet the strict definition of AFS of combining the growth of trees with harvesting crops or pasture, but if preferred, they can easily be managed as AFS. Therefore, were consider nut orchards to be a kind of AFS.

1.2 Research objective

The object of this study is to develop future pathways at the level of parcels to analyse, from the perspective of global climate mitigation, C sequestration in *Corylus* and *Juglans* orchards on sandy and loamy soils in the (temperate) province of Gelderland in the Netherlands compared to previous agricultural management systems. The results of this study can be used by actors like the Dutch government and policy makers of the province of Gelderland to consider whether or not planting nut orchards on sandy and loamy soils can make a valuable contribution to offsetting a part of CO_2-level rise and increased soil quality. Results can also be used to model the contribution of C-sequestration by new nut orchards to the obligations of the Dutch government on meeting the Paris goals.

1.3 Research question

At which rate do Carbon stocks, Carbon fluxes and the quality of Soil Organic Carbon change after converting agricultural grassland respectively cropland into *Corylus* and *Juglans* orchards on sandy and loamy sand soils in the temperate zone of Gelderland?

1.3.1 Sub-questions

1a. Which characteristics of carbon sequestration in nut orchards, cropland and grasslands are representative and easily measurable?

1b. Which physical, chemical and biological characteristics of soil quality are representative and easily measurable?

2a. How large are C-stocks and C-fluxes in various nut orchards, soils and comparable previous agricultural management systems at sandy and loamy sand soils in Gelderland?

2b. What is the quality of the soil organic matter under nut orchards and comparable cropland respectively grassland at sandy and loamy sand soils in Gelderland?

3. How does a model to predict future pathways for C-sequestration in soil and biomass look like for *Corylus* and *Juglans* orchards at sandy and loamy sand soils in Gelderland?

2 Study area: Temperate Zone

The study was conducted at nut orchard ‘t Joostenhuus in Breedenbroek, Gelderland the Netherlands (latitude 51°88’09’’531 and longitude 6°44’64’’004, elevation 15 m), and its direct vicinity (Figure 4). The mean air temperature is 10.13 °C (Weerstatistieken, n.d.) and annual precipitation is 770 mm (Heijboer & Nellestijn (2002) as cited in Grondwaterformules.nl (2020)). The area of study is located in the temperate agro ecological zone (AEZ).

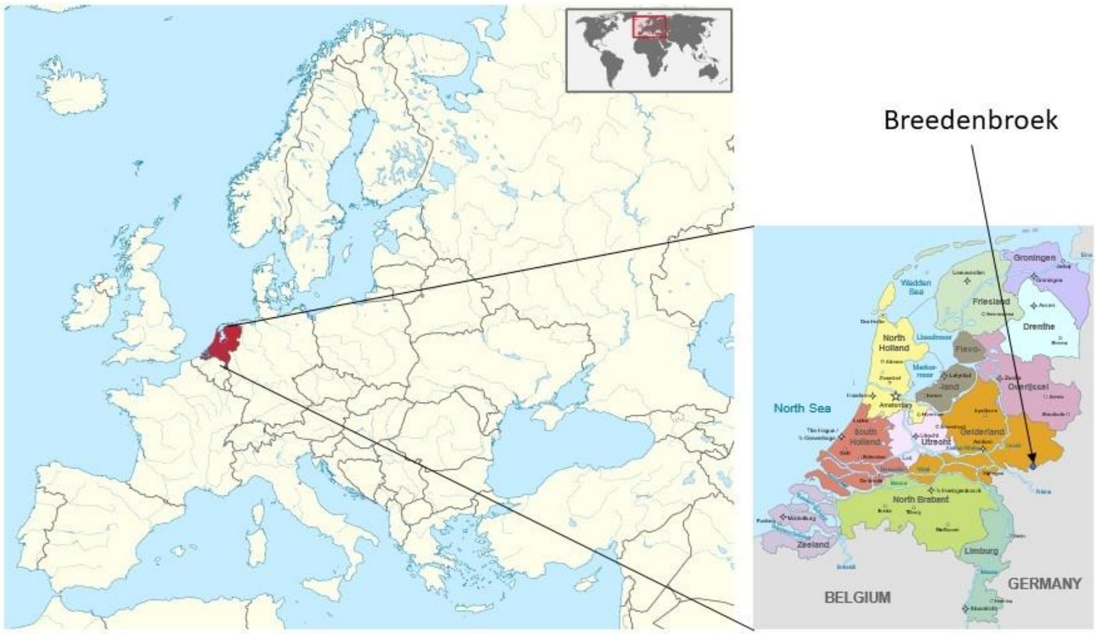

Figure 4 Study area location (Image: Wikimedia Commons)

The nut orchard in Breedenbroek covers about 6 ha and covers various parcels (Appendix A.1). Most of the nut orchard is planted with *Corylus* trees (*Corylus avellana*) (Table 3) in rows at regular distances, with an age of 8, 23.5 or 25.5 years. The rows at the parcels C1993 and C2011 have a north-northeast (NNE) orientation and rows at parcel C1995 have an north-by-east (NbE) orientation. The orchard also contains 4 large *Juglans* trees (*Juglans regia*) which are planted between 15 and 124 years ago (the youngest tree, from 2004, is excluded from the study). All *Corylus* and the youngest *Juglans* trees have been planted on a soil, previously mainly managed as cropland, while the oldest *Juglans* have been planted on a soil previously managed as grassland (Table 3). The western part of the study area is located on a loamy azonal soil and the eastern part is located on a brown podzolic soil (Appendix A.2).

Table 3 Parcel characteristics (additional information can be found in Appendix A.2; Table 41).

Parcel	Tree species (variety)	Soil type (code[2])	Soil texture & pH (clay:silt:sand % from soil, pH)	Previous land use (decades before planting)	Current vegetation (herb layer)	Trees planted in	Sowing year trees
Ar	None	Loamy azonal soil (fkZn23g)	Loamy sand (8:17:72, pH 5.1)	Mixed (grass/ cropland)	Maize/bare/ winter rye		
C2011	*Corylus avellana*	Loamy azonal soil (Zn23)	Sand/loamy sand (6:12:79, pH 5.0)	Mixed (grass/ cropland)	50% bare soil, 50% grass	2011/ 2012	±2009
C1993	*Corylus avellana*	Loamy azonal soil (Zn23)	Sand/loamy sand (6:13:78, pH 5.8)	Mixed (grass/ cropland)	25% bare soil, 75% grass	1993/ 1994	±1991
GrS	None	Brown podzolic soil (cHn23)	Sandy (4:12:78, pH 4.7)	Grassland	Grass		
J1895	*Juglans regia*, week growing variety	Brown podzolic soil (cHn23)	Sandy (3:9:80, pH 5.2)	Unknown	Grass	1895	1895
GrNE	None	Brown podzolic soil (cHn23)	Sand/loamy sand (3:16:77, pH 6.3)	Mainly grassland	Grass		
J1976	*Juglans regia* (Buccaneer)	Brown podzolic soil (cHn23)	Sand/loamy sand (5:15:76, pH 5.2)	Mixed (grass/ cropland)	Grass	1976	1971
J1966	*Juglans regia* (seedling from J1895)	Brown podzolic soil (cHn23)	Sand/loamy sand (3:15:77, pH 4.8)	Grassland	Grass	1966	1966
C1995	*Corylus avellana*	Brown podzolic soil (cHn23)	Sand/loamy sand (3:15:77, pH 5.4)	Mixed (grass/ cropland)	25% bare soil, 75% grass	1995/ 1996	±1993

Future pathways of C-sequestration at the study area might be influenced by climate change. The Klimaateffectatlas (n.d.) predicts that in the period from 2020 to 2050, climate at the study area might change: e.g. number of frost days per year (min. < 0°C) from 60-70 to 20-30, summer precipitation from 200-225 mm to 175-200 mm and the number of tropical days (max. ≥ 30°) from 3-6 to 15-18. According to Wertheim (1981); Wertheim and Goedegebure (1987) the fruit production of *Corylus* and *Juglans* is vulnerable to night frost in spring and to low temperatures in the growing season, and at the other range of temperature hot summers (and drought) will have a negative effect on fruit production too. This makes it complex to make predictions about the ecological and economic feasibility of nut orchards at the study area when climate change proceeds.

[2] Dutch soil classification

3 Methodology: conceptual model

The method of research was to describe changes in time in C-stocks and soil quality in nut plantations, as chronosequences. This mixture of quantitative and qualitative research made it mixed method research. The research can also be described as a C-budget approach in the form of a case study. The changes in C-stocks were translated into sequestration rates.

3.1 Chronosequences

Chronosequences are locations which had a comparable land use management under comparable environmental conditions, but with different ages. The most accurate results can be obtained by measuring stocks over a period of decades, with intervals of several years. Since this takes a lot of time, researchers often make use of chronosequences. Lal (2005), Walker, Wardle, Bardgett, Clarkson, and Sveriges (2010) and H. Zhang, Wang, Zeng, Du, and Zeng (2017) carried out their studies on C-sequestration with the use of chronosequences.

The nut orchard of our study contains nut trees of different ages (Table 3), including some control (reference) parcels, which made the location very suitable for a chronosequence comparison, so the study was carried out with the use of chronosequences. In the study area of the nut orchard, at various locations C stocks were measured and compared. It is valid to compare results with a control parcel, which was sampled at another moment then the moment of planting, because Conijn and Lesschen (2015) conclude that in the Netherlands SOC stocks are stable beneath cropland and slowly increasing under grassland. The idea behind chronosequences is that samples will all be collected at the same time, and samples from comparable locations will be grouped in a logical sequence.

Lesschen et al. (2012) and Paul et al. (2002) stress that every form of land use, vegetation and soil types has its own capacity of capturing or releasing CO_2. Our study area contains different types of previous land use, different tree species and different soil textures. The chronosequences were compiled by combining characteristics of the soil (Table 3 & Appendix C.3), historic management (Appendix A.5) and current main vegetation (Table 4) into four groups of parcels (Table 4).

Table 4 Chronosequences at study area Breedenbroek (each colored cell is a parcel, with its code in it. The letter J in the name of the chronosequence parcels stands for Juglans and the letter C stands for Corylus. The parcels with the same color together make a chronosequence, which name is rendered in the first column).

Year of planting	**1895**	**1966**	**1976**	**1993/1994**	**1995/1996**	**2011**	**Control parcel (2019)**
Tree age (in 2019)	124	53	43	25,5	23,5	8	0
Tree spec.	*Juglans*	*Juglans*	*Juglans*	*Corylus*	*Corylus*	*Corylus*	
Chronosequence							
J-sandy	J1895						GrS
J-loamy		J1966	J1976				GrNE
C-loamy brown					C1995		GrNE
C-loamy hydro				C1993		C2011	Ar

3.2 C-budget approach

The C-budget approach could only be applied at our study area when the different C-stocks were well defined (Figure 5). We distinguished **soil C-stock** and **biomass C-stock.**

Soil C-stock was divided into three different groups: soil organic carbon (SOC), belowground biomass C-stock (BGB) and soil inorganic C (SIC). Within SOC Lal (2005) distinguishes three different fractions: the labile, intermediate and passive fraction. The distribution of these fractions tells us more about the quality of the SOC (Rovira, Jorba, & Romanyà, 2010). From Lal (2018) we learn that the SOC stock is positively related to soil quality, soil health, aggregate stability and biomass productivity.

BGB was divided in two main subgroups: in accordance with Lorenz and Lal (2014), who defined fine roots and Borden, Isaac, Thevathasan, Gordon, and Thomas (2014) who defined coarse roots. Carbon captured in living organisms which are too large to be measured under SOC and are no roots, was left out of consideration, because according to Locher and De Bakker (1990, p. 109) this it is a relatively small part of the total SOC. Research of Holtkamp (2010) supports the proposition that the amount of carbon in this category, like fungi and small animals in the soil, is small compared to the total SOC. Based on the research of Van Eekeren, Bokhorst, Deru, and de Wit (2014) we estimated the amount of non-root living BGB at 1% of the SOC.

Since the SIC fraction in soil is not very active (FAO, 2019a, p. 28) and is expected to be a small percentage of SOC we did not elaborate the SIC content in detail.

We split the aboveground biomass C-stock into four groups of C-stocks. The division was based on the study of H. Zhang et al. (2017) who defined many subgroups of aboveground biomass C, which we aggregated to the next four groups of C-stocks: carbon in litter, wood (branches and stems), foliage & fruits and herbs & grasses. Subsequently the subgroup of wood was split into living wood and harvested wood/prunings, to be able to model at the right detail.

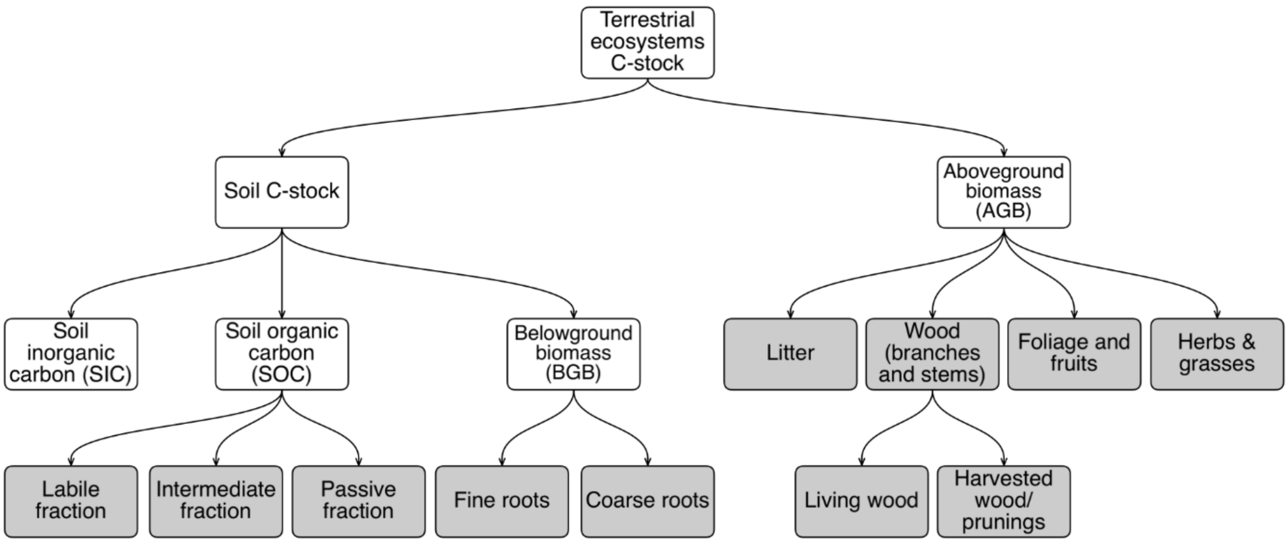

Figure 5 Carbon stocks in terrestrial ecosystems (based on the diagram of Lal (2005). All grey rectangles are added compared to Figure 2).

To calculate the C-stock change rate (r_c, Mg C ha^{-1} yr^{-1}), i.e. the C-flux, we used the same formula as Luo, Feng, Luo, Baldock, and Wang (2017):

$$Cflux = \frac{Cstock_{t+\Delta t} - Cstock_t}{\Delta t} \qquad (1)$$

Where,

Cflux = C-flux (Mg C ha^{-1} yr-1)

Cstock = the C-stock at time t or t + Δt (Mg C ha^{-1})

Δt = time (years)

Which we compared to the next formula:

$$Cflux = C_{in} - C_{out} \qquad (2)$$

Where,

Cflux = C-flux (rate at which the C-stock changes per year)

C_{in} = C-stock inflow (Mg C ha^{-1} yr-1)

C_{out} = C-stock outflow (Mg C ha^{-1} yr-1)

C-stocks do not develop autonomous, but are subject to various fluxes (Figure 1). Therefore, it was necessary to visualise and quantify these fluxes. The driving force of C-sequestration is photosynthesis which produces carbon in leaves, that runs through the tree and is eventually sequestered in all parts of the tree. Parts of the tree store the carbon in a stable stock and other parts of the carbon stored in the tree fall off and finally decompose and return to the to the atmosphere or are transformed into SOC. C-fluxes into or out of the orchard, like the application of manure and chalk or sold fruits, were quantified too.

3.3 Data types

Data types as discussed in the previous paragraph were further divided in categories to order data collection (Figure 6). This categorisation was attuned to the categories the Intergovernmental Panel on Climate Change (IPCC) has to report on in relation to GHG emissions: SOC, AGB, BGB, dead wood (absent in our study area), litter and harvested wood products (crop and prunings) (IPCC, 2006). Figure 5 only contained C-stocks, though between these stocks run fluxes, so in Figure 6 we added C-fluxes to complete the conceptual model.

Data on C-stocks and C-fluxes had to be collected from different sources (between brackets the corresponding colours in Figure 6):

I. Field samples collected in every parcel and analysed in a laboratory[3] (red rectangles);
II. Data collected by field survey on vegetation and soil quality (yellow: data collected at a complete parcel and green: data collected at sub-parcel-level);
III. Data based on oral sources and field data (purple rhombi);
IV. Data based on literature (grey rectangles).

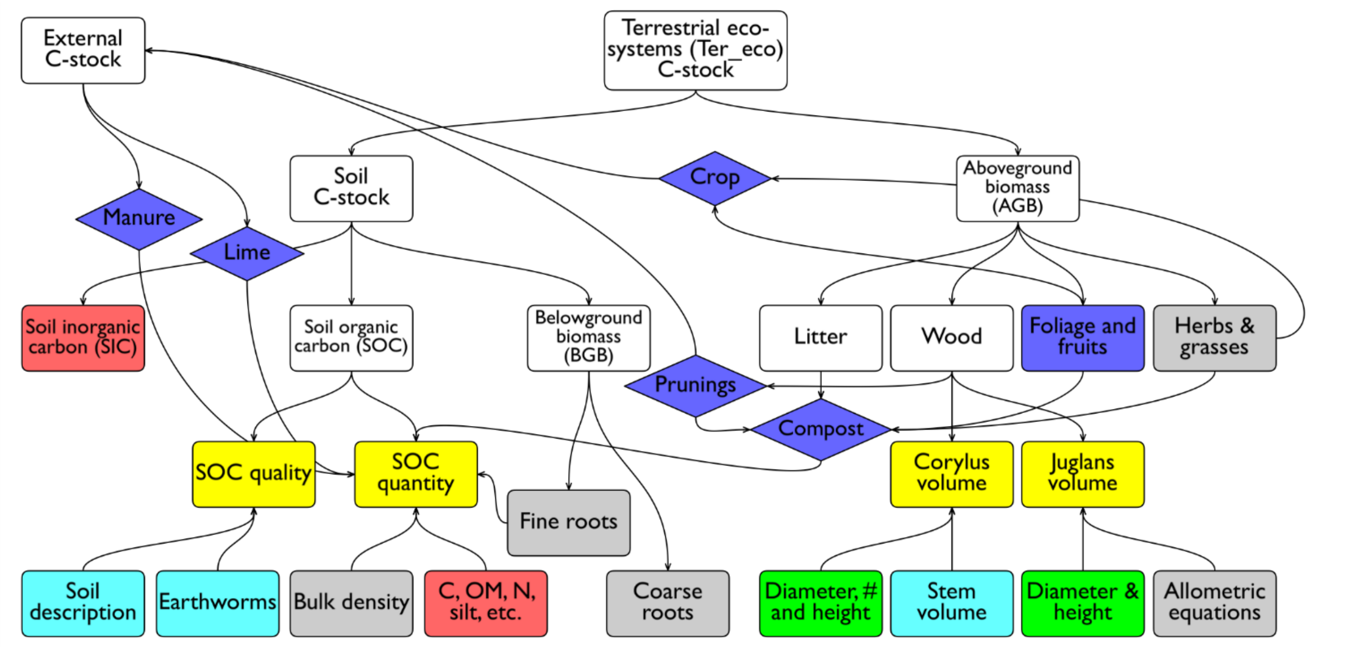

Figure 6 Data types and data collection (rectangles= stocks, rhombi= fluxes; further details are elaborated in the text above this figure. Partly based on the diagram of Lal (2005)).

[3] All laboratory analysis in 2018/2019 has been done by the company Eurofins from Wageningen (http://www.eurofins-agro.com) and refer to analysis of dry soil. All samples have been processed single, except for the Phosphor-stock.

4 Methodology: materials and techniques

This chapter discusses the techniques that were applied to collect the data on C-stocks and C-fluxes. Stocks could easily be quantified, either by laboratory analysis, or by field measurements. Fluxes on the other hand are more variable, and complex to quantify. The size of the fluxes was based on field data, and the knowledge and administration of the owner of the nut orchards. Literature study was used to add missing information.

4.1 Soil sampling and soil quality

The most important parameters to measure in relation to the SOC stock are SOC and SOM. The SOC and SOM are determined as a fraction, so if we know the bulk density the exact amount of carbon at a hectare can be calculated. Measuring bulk density is also important, because, according to Locher and De Bakker (1990) a lower bulk density corresponds with a higher SOM level. Other important parameters to indicate the SOC stock, the quality of soil, and in particular the quality and stability of the SOC are (Table 5):

- A soil with a high clay-humus fraction results in more stable SOM with a slower SOM breakdown rate, so the clay-humus fraction is an indicator of SOM quality (Locher & De Bakker, 1990). A higher Clay-humus ratio corresponds with more SOM (Cornell University, 2007).
- The clay-humus-ratio is closely related to the cation exchange capacity (CEC). In sandy soils a higher CEC is positively correlated to the amount of SOM. The CEC also tells us more about the quality of SOM; a higher CEC corresponds with older, thus more stable, SOM (Locher & De Bakker, 1990).
- Soil crusting is an indicator of a good soil quality that might be related to the amount of SOC. A higher SOM will reduce problems with soil crusting (Bodemacademie, n.d.).
- The breakdown ratio of SOM is an important indicator of SOM stability (SOM-quality).
- The moisture retaining capacity and the pF-appending point are important soil quality indicators that have a positive correlation with the SOC concentration (Lal, 2018).
- Nitrogen (N) (in the C/N ratio), phosphorus (P) (in the C/P ratio) and sulphur (S) (in the C/S ratio) are other parameters that indicate a good SOM-quality. The importance of the C/N ratio as an indicator of C-stability is supported by Lorenz and Lal (2014).
- Soils with a higher pH have a higher amount of SOM (very low and very high pH excepted) (Locher & De Bakker, 1990).
- Hot-water extractable carbon (HWC) is positively correlated to the soil microbial biomass, microbial nitrogen, mineralizable N and the total C-stock in the temperate climate and can be used as an indicator of soil quality (Ghani, Dexter, & Perrott, 2003).
- Rising SOM levels lead to an increase of micro-organisms, so the amount of micro-organisms (measurable by respiration) is an indicator of the SOM level (Locher & De Bakker, 1990).
- Earthworms are important for many processes that relate to SOM, e.g. transforming fresh organic matter (OM) into more stable forms of SOM or SOC, the distribution of OM/SOM and the distribution of fungi and bacteria that are important to SOM processes (Van Eekeren et al., 2014). Therefore, earthworms are an indicator of SOM quality.
- The distribution of SOC fractions (labile, intermediate vs. passive) also tells us more about the quality of the SOC (Rovira et al., 2010), but is not easy to measure, so measuring the fraction distribution was not added to the list of our parameters.

For each relevant parameters, the objective, scale, data source and research category were elaborated in a protocol (Table 5). Our list of parameters largely corresponds with the list of frequently used indicators for soil quality as elaborated by Bünemann et al. (2018) and Hanegraaf, van den Elsen, de Haan, and Visser (2019). All parameters have been summarized and target values were collected (*Table 6*), to which our results have been compared.

Table 5 Sampling protocol and research category of the main soil parameters (the colors refer to the source of the data: red= data collected at specific points in every parcel, bright blue= data collected at specific points in some parcels, grey= literature. All samples analyzed by a certified laboratories).

Parameters	Category	Objective	Scale	Protocol [Method as applied by laboratory]	Data source
Soil Organic Matter (SOM)	Physical	Soil quality	Sample^{-1}	Estimating the amount of C loss of a soil sample after heating, as described by Nair (2012) [NIRS]	Samples
SOC	Physical	SOC stock	Sample^{-1}	Estimating amount of C loss of a soil sample after heating, as descry. by Nair (2012) [COR6]	Samples
Clay-humus	Physical	Soil quality	Sample^{-1}	Examination of samples in a laboratory [NIRS]	Samples
CEC	Physical	Soil quality	Sample^{-1}	Examination of samples in a laboratory [NIRS]	Samples
Soil crusting	Physical	Soil quality	Sample^{-1}	Examination of samples in a laboratory	Samples
SOM annual breakdown	Physical	Soil quality	Sample^{-1}	Examination of samples in a laboratory	Samples
SOM quality	Physical	Soil quality	Sample^{-1}	Examination of samples in a laboratory	Samples
Moisture retaining capacity	Physical	Soil quality	Sample^{-1}	Examination of samples in a laboratory	Samples
pF-appending point	Physical	Soil quality	Sample^{-1}	Examination of samples in a laboratory	Samples
C/N-ratio	Phys./chem.	Soil quality	Sample^{-1}	Can be collected by applying the method of chemo-destructive fractionation (nowadays mostly done by spectral analysis with light) (Lorenz & Lal, 2014).	Samples
pH	Chemical	Soil quality	Sample^{-1}	Chemical examination in a laboratory [NIRS]	Samples
N (stock)	Chemical	Soil quality	Sample^{-1}	Examination of samples in a laboratory [NIRS]	Samples
N (delivery cap.)	Chemical	Soil quality	Sample^{-1}	Examination of samples in a laboratory	Samples
P (stock)	Chemical	Soil quality	Sample^{-1}	Examination of samples in a laboratory [NIRS]	Samples
S (stock)	Chemical	Soil quality	Sample^{-1}	Examination of samples in a laboratory [NIRS]	Samples
Micro biologic. act.	Biological	Soil quality	Sample^{-1}	Examination of samples in a laboratory [NIRS]	Samples
HWC	Physical	Stock+qual	Sample^{-1}	Examination of samples in a laboratory [HWC]	Samples
Bacteria aerobe	Biological	Soil quality	Sample^{-1}	Examination of samples in a laboratory [CFU]	Samples
Bacteria anaerobe	Biological	Soil quality	Sample^{-1}	Examination of samples in a laboratory [CFU]	Samples
Fungi, yeasts	Biological	Soil quality	Sample^{-1}	Examination of samples in a laboratory [CFU]	Samples
Earthworms	Biological	Soil quality	Sample^{-1}	Counting and weighing amount of earthworms in: 0-30 cm depth; in a volume of 30*30*30 cm soil; 30-60 cm; that emerged after pouring a mustard-water solution into dug hole. Based on Peigné, Huber, and Pfiffner (2017)	Field work
Soil description	Administra-tive	Soil quality	Parcel^{-1}	Description of profile pits, made by spade resp. hand auger	Field work
Manure & fertilisers	Administra-tive	C-flux	Parcel^{-1}yr-1	Budgeting manure and other fertiliser fluxes, based on values of CDM (2017)	Oral + literature
Lime	Administra-tive	Nutrient and C-flux	Parcel^{-1}yr-1	Budgeting all fertiliser fluxes (e.g. lime)	Oral + literature
Bulk density	Physical	SOC stock	Sample^{-1}	The bulk density is not measured but estimated by the laboratory based on chemical and physical characteristics (method unknown)	Samples

Table 6 Target values for parameters that indicate quality of soil and SOM.

Parameter	Unit	Target value tree nursery (Eurofins, n.d.)	Target value good (Locher & De Bakker, 1990)	Quality importance	Remarks
C/OM	%	0.45-0.55		SOM & soil	
OM annuel breakdown	%		<2% (the mean in Nl)	SOM & soil	Lower SOM-annual breakdown means better quality SOM (Locher & De Bakker, 1990)
C/N	dimension-less	13-17	≥10	SOM & soil	Range of Eurofins (2018) is applied, otherwise all values would have been marked as good, which is less distinctive. A higher ratio corresponds with a higher SOM-quality (Locher & De Bakker, 1990)
C/S	dimension-less	50-75	≥100	SOM & soil	We applied a combination of Eurofins & Locher and De Bakker (1990), because the target of Locher and De Bakker (1990) was so high that only one parcels would have scored within target range. Higher ratio corresponds with higher SOM-quality (Locher & De Bakker, 1990)
C/P	dimension-less		≥100	SOM & soil	Target A higher ratio corresponds with a higher SOM-quality (Locher & De Bakker, 1990)
Clay-humus	Mmol+/kg	44-93 (Eurofins, personal communi-cations, May 2, 2019)		SOM & soil	Soil-dependent, though a high clay-humus rate indicates that it is not easy to break down SOM (Locher & De Bakker, 1990)
CEC	%	>95		SOM & soil	a high CEC is pos. correlated to SOM-quality (Lorenz & Lal, 2014)
HWC	mg/kg			SOM & soil	a high HWC is positively correlated to soil quality and total C-stock (Ghani et al., 2003), target value -dairy 700-2300 for farming at sand- (Hanegraaf et al., 2019)
Earthworms	kg/ha			SOM & soil	700 kg ha^{-1} at a cattle farm in Friesland Van Eekeren et al. (2014)
N-stock	kg N/ha	3200-4700 until 4560-6660 (Eurofins, personal communi-cations, May 2, 2019)		Soil	Soil-dependent
N-delivery cap.	kg N/ha	95-145		Soil	
pH	pH	5.5-6.3 (Eurofins, personal communi-cations, May 2, 2019)		Soil	Soil-dependent, though high pH in general corresponds to higher SOM-stock (Locher & De Bakker, 1990)
Soil crusting	grade	6.0-8.0		Soil	

All soil sampling was based upon strata, according to recommendations of FAO (2019a) (Appendix B.1).

4.2 SOC

4.2.1 SOC stock

To answer the research questions, it is necessary to scale all data to weights per hectare (e.g. Mg ha^{-1}), since these units are easily comparable and generally used to present results.

The amount of SOC at a specific depth was derived from C-concentration data:

$$SOCstock_{depth} = \frac{SOC_{conc\_depth}}{10^2} BD * 10^{-6} * V_{0-30} \qquad (3)$$

Where,

$SOCstock_{depth}$ = SOC stock at a specific 30 cm thick layer (Mg C ha^{-1})

SOC_{conc_depth} = C-concentration at a specific depth (%)

BD = bulk density of the soil (g L^{-1})

V_{30cm} = Volume of a 30 cm thick layer of soil (L ha^{-1})

The soil mass was based on the share of soil organic matter:

$$Soil_{mass} = \frac{100}{som} SOM_{mass} \qquad (4)$$

Where,

$Soil_{mass}$ = mass of a 30 cm thick layer of soil (Mg ha^{-1})

som = share of soil organic matter (%)

SOM_{mass} = mass of soil organic matter at a 30 cm thick layer of soil (Mg ha^{-1})

For each parcel the soil bulk density was determined with the help of equation 4. All SOC stock calculations were based on the mean of these bulk densities (see Sensitivity analysis on bulk density for additional information).

4.2.2 SOC flux

The SOC flux was based on the SOC-stock accumulation at a parcel and can be seen as the incremental growth of the SOC-stock. Therefore, parcel values were compared to a control parcel within the same chronosequence (Cardinael et al., 2017):

$$\Delta SOCstock = SOCstock_{plot} - SOCstock_{ref} \qquad (5)$$

Where,

ΔSOCstock = SOC stock change (Mg C ha^{-1})

$SOCstock_{parcel}$ = SOC stock in the soil of the agroforestry parcel (Mg C ha^{-1})

$SOCstock_{ref}$ = SOC stock in the soil of the agricultural control parcel (Mg C ha^{-1})

The SOC flux was calculated with the following equation:

$$SOCflux = \frac{\Delta SOCstock}{\Delta t} \qquad (6)$$

Where,

SOCflux = flux (increment) of C in the soil (Mg ha^{-1} yr^{-1})

ΔSOCstock = SOC stock change (Mg C ha^{-1})

Δt = number of years since planting (years)

Palma et al. (2007) assumed the SOC flux in cropland to be 0 Mg ha^{-1} yr^{-1}. Van Eekeren and Zaneveld-Reijnders (2011) found various SOC fluxes for the top 30cm for different sequences of grassland and maize in the Netherlands, though on average the C-flux was about 0 Mg ha^{-1} yr^{-1} too. Therefore, we assumed the SOC-flux in cropland (Ar) to be 0 Mg ha^{-1} yr^{-1}.

For the GrS parcel, which has continuously been used as grassland, we assumed the SOC flux to be 0.49 Mg ha^{-1} yr^{-1} (based on Van Eekeren and Zaneveld-Reijnders (2011); 1.014 Mg SOM ha^{-1} increase in 30 years over the top 30 cm). The SOC flux at the GrNE parcel was expected to be lower (0.38 Mg C ha^{-1} yr^{-1}), because this parcel was managed in a rotation comparable to a 3 years 100% grass and 1 year maize rotation (Van Eekeren & Zaneveld-Reijnders, 2011).

4.3 Biomass

4.3.1 Biomass sampling

The total Biomass C-stock is the sum of the BGB and the AGB. For each type of biomass data, the objective, scale, data source and research category were elaborated in a protocol (Table *7*7 & Table *8*8).

Table 7 Sampling protocol and research category of the main biomass parameters.

Parameter	Objective	Scale	Protocol and data source	Research category
Coarse and fine roots	Belowground biomass C-stock	/parcel	Estimating relative to tree volume with equations	Literature
Tree diameter, # trees and height	Stem volume (biomass C-stock)	/tree (or group of trees)	*Corylus:* selective *Juglans*: all trees	Field data
Stem volume *Corylus*	Aboveground biomass C-stock	/tree	C1993, C1995: felling and weighting a model tree and multiply the result with the number of trees/ha C2011: allometric equations	Field data
Stem volume *Juglans*	Aboveground biomass C-stock	/tree	With the use of allometric equations, based on diameter	Literature
Litter	Aboveground biomass C-stock	/ha	Literature study	Literature
Foliage and fruits 1	Aboveground biomass C-stock	/parcel	Literature study and field data	Literature + oral/field data
Foliage and fruits 2	Tree vitality	/parcel	Leaf sampling. Samples from 3 varieties (per variety: a mix of 50 leaves, 5/tree)	Samples
Herbs and grasses	Aboveground biomass C-stock	/ha	Literature study	Literature
Crops	Aboveground biomass C-flux	/ha/yr	Budgetting annual nut, grass, maize and other crop flows, based on Wageningen University & Research (2018), Handboek Bodem en Bemesting (n.d.), Brkic (n.d.) and CDM (2017)	Literature + oral/field datal
Prunings/thinnings	Aboveground biomass C-flux	/ha/yr	Budgetting annual pruning flows and thinned wood volume	Oral/field data
Compost	Aboveground biomass C-flux	/ha/yr	Budgetting annual flows turned into compost (fruits, foliage, grass, branches)	Oral/field data

Corylus is not a self-pollinating tree species, so a *Corylus* orchard needs to contain different tree varieties at short distances. The orchard of study does contain different varieties of *Corylus* at each parcel (Appendix A.3). Each variety has its own growth speed and some varieties produce much more fruits (nuts) than others. Therefore, we decided to involve all *Corylus* varieties in our study.

Table 8 Sampling protocol of Corylus trees

	C2011	C1993	C1995
DBH	Non-selective (every 10th tree from the south)	Non-selective (every 2th)	All
Tree height	Selective	Non-selective (each row, mean DBH)	Non-selective (each row, mean DBH)
Model tree	DNA	Selective (a representative variety; Gunslebert)	Selective (a representative variety, Gunslebert)

4.3.2 *Biomass C-stock*

The biomass C-stock was divided in two groups: biomass in *Corylus* & *Juglans* and biomass in herbs & grasses, which were both subdivided in AGB and BGB. A method for litter was not elaborated, because the litter layer is absent for most of the year at the study area.

Carbon in biomass was calculated by multiplying the DM weight with the c-concentration:

$$C_{type} = DM_{type} * c \qquad (7)$$

Where:

C_{type}= carbon weight of a specific type of biomass (g kg^{-1})

DM_{type}= dry matter weight of a specific type of biomass (g kg^{-1})

c= carbon concentration of the specific type of biomass (g kg^{-1}) (Table 99)

Table 9 Carbon content of various types of biomass (for Corylus fruits we used the same C-content as for Juglans).

Type of biomass	Carbon (g kg^{-1} dry matter)	Source
Corylus	484.1	Lamlom and Savidge (2003), mean for hardwood
Juglans (fruits)	486.4	H. Zhang et al. (2017)
Juglans (foliage)	464.7	H. Zhang et al. (2017)
Juglans (branches)	437.2	H. Zhang et al. (2017)
Juglans (stems)	461.3	H. Zhang et al. (2017)
Juglans (fine roots)	452.3	H. Zhang et al. (2017)
Juglans (coarse roots)	452.3	H. Zhang et al. (2017)
Grass, maize	0.965*450	0.965: Brkic (n.d.), 450: CDM (2017)
Bovine slurry	347.3	CDM (2017)

Trees

The biomass in trees could not be calculated with the help of a single equation. Each tree species has its own growth characteristics and the calculation of AGB and BGB required different equations too (Table 10). Another reason for a unique calculation for each parcel was the spread in age and the number of trees at a parcel; e.g. some parcels had been thinned in the past and others were not, and in some parcels we could base our calculations on felled trees, and in others we could not.

Table 10 Calculation of biomass in trees (additional information in Appendix B.2).

Parameter	Tree species (parcel)	Equation	Source
Dry matter_tree	*Corylus & Juglans*	$DM_{type} = FM_{type} * (1 - m)$ (8)	Paul, Roxburgh, and Larmour (2017)
Fresh matter_tree	*Corylus* (C1993, C1995)	$FM_{tot\_trees} = FM_{thin} * (\frac{100}{p_{thin}})$ (9)	
Fresh matter_parcel	*Corylus* (C1993, C1995)	$FM_{mean\_plot} = \frac{FM_{ref\_mean\_plot}}{FM_{ref\_model}} * FM_{model}$ (10)	
Fresh_matter_ control	*Corylus* (C1993, C1995)	$FM_{ref} = 0.0156DBH^{1.974} + 0.0041DBH^{3.063} + 0.0861DBH^{2.381}$ (11)	He et al. (2018)
Foliage share	*Corylus* (C1993, C1995)	$bc_{Corylus\_mean} = \frac{(bc_{lit\_1} + bc_{lit\_2} + bc_{lit\_3})}{3}$ (12)	
Dry matter_tree	*Corylus* (C2011)	$DM_{AGB-tree} = a * h * DBH^2 + b$ (13)	Albert, Annighöfer, Schumacher, and Ammer (2014)
C-stock_BGB	*Corylus* (2011)	$Cstock_{BGB-tree} = e^{-1.3267+0.8877xln(Cstock_{AGB-tree})+0.1045xln(Age)}$ (14)	Cairns, Brown, Helmer, and Baumgardner (1997)
Fresh matter_tree	*Juglans*	$FM_{AGB-tree} = 0.0156DBH^{1.974} + 0.0041DBH^{3.063} + 0.0861DBH^{2.381}$ (15)	He et al. (2018)
Fresh matter_coarse roots	*Juglans*	$FM_{BGB-coarse} = 0.0166DBH^{2.565}$ (16)	He et al. (2018)

Herbs and grasses

The herbs and grasses of GrNE and GrS are likely to be dominated by *Lolium perenne* (English rye-grass). Cougnon et al. (2013)[4] as cited in Cougnon et al. (2017) found a dry BGB of 1382 g m^{-2} (13.82 Mg DM ha^{-1}) for Lolium perenne on north-west European sandy soils.

Kutschera, Lichtenegger, and Sobotik (2009) show that the biomass of 14 months old *Lolium perenne* grassland is much larger than that of 10 weeks old grass. The growth of grass biomass is limited though, because Van Eekeren et al. (2008) reports that the amount of roots in three year old grassland is significantly higher than in 38 year old grassland. We therefore assume that the biomass of grass is at its maximum at the age of three, after which the biomass will decrease until the age of 38 years. A continuous decrease of the AGB and BGB is not likely, since there still was grass under the oldest Juglans after more than 100 years.

We applied the following equations to determine the BGB of grass (Table 111):

Table 11 Age based equations to calculate the amount of dry matter in below ground biomass (BGB) of grass and cropland.

Agricultural use	Age	Equation/input value	Number
Grassland	0 – 3	$DM_{BGB-grass}$ = Age * 4.6067	(17)
Grassland	3-38	$DM_{BGB-grass}$ = 13.820 - ((Age-3) * 0.15982)	(18)
Grassland	>38	$DM_{BGB-grass}$ = 8.2262	(19)
Cropland	0-1	2.3 Mg FM ha^{-1} (Conijn & Lesschen, 2015), annually refreshed -> stock = flux	

Where,

$DM_{BGB-grass}$ = mass of BGB of grass (Mg DM ha^{-1})

Age = number of years since sowing grass (years)

FM = fresh matter

[4] original source not available

Based on the values of Verschot et al. (2006, p. 6.27) we generated the next equation to calculate the AGB in Cold Temperate to Wet conditions:

$$DM_{AGB-grass} = \frac{2.4}{11.2} * DM_{BGB-grass} \qquad (20)$$

Where:

$DM_{AGB\text{-}grass}$ = mass of AGB of grass (Mg DM ha^{-1})

$DM_{BGB\text{-}grass}$ = mass of BGB of grass (Mg DM ha^{-1})

The C-stock in grass was calculated by multiplying the DM stock with the share of OM resp. carbon:

$$Cstock_{AGB-grass} = DM_{AGB-grass} * f_{DM-OM} * f_{OM-C} \qquad (21)$$

Where,

$Cstock_{AGB\text{-}grass}$ = aboveground biomass of grass (Mg C ha^{-1})

$DM_{AGB\text{-}grass}$ = mass of AGB of grass (Mg DM ha^{-1})

$f_{DM\text{-}OM}$ = share of OM in DM = 0.965 (Brkic, n.d.)

$f_{OM\text{-}C}$ = share of C in OM = 0.45 (CDM, 2017)

Total biomass
The total biomass C-stock is the sum of biomass in BGB and AGB of trees and grasses:

$$Cstock_{TB} = Cstock_{BGB-trees} + Cstock_{AGB-trees} + Cstock_{BGB-grass} + Cstock_{AGB-grass} \qquad (22)$$

Where,

$Cstock_{TB}$ = mass of all biomass (Mg C ha^{-1})

$Cstock_{BGB\text{-}trees}$ = belowground biomass of trees (Mg C ha^{-1})

$Cstock_{AGB\text{-}trees}$ = aboveground biomass of trees (Mg C ha^{-1})

$Cstock_{BGB\text{-}grass}$ = belowground biomass of grass (Mg C ha^{-1})

$Cstock_{AGB\text{-}trees}$ = aboveground biomass of grass (Mg C ha^{-1})

4.3.3 Biomass C-flux

All FM fluxes of biomass were calculated with the following equation:

$$I_{C\_type} = \frac{\Delta FMstock_{type}}{\Delta t} \qquad (23)$$

Where,

I_{C_type} = flux (increment) of FM for a type of biomass (Mg FM ha^{-1} yr^{-1})

$\Delta FMstock_{type}$ = FM stock change of a type of biomass (Mg FM ha^{-1})

Δt = number of years since planting (years)

Wood

The annual increment of woody biomass until the first thinning of *Corylus* orchards was based on the wood volume that was removed during the first thinning:

$$I_{a1} = (FM_{thin} * (\frac{100}{p_{thin}}) * Age^{-1} + FM_{ap} \qquad (24)$$

Where:

I_{a1}= annual increment of woody biomass in term 1 (Mg FM ha^{-1} yr^{-1})

FM_{thin}= mass of cut trees (Mg FM ha^{-1})

p_{thin}= percentage of trees cut

FM_{ap}= annual cuttings/annually pruned wood (Mg FM ha^{-1} yr^{-1})

Age= number of years since planting (years)

The annual increment of woody biomass between the first and second thinning of *Corylus* orchards was based on the wood volume that was removed during the second thinning:

$$I_{a2} = \frac{FM_2 - FM_1}{\Delta t} + FM_{ap} \qquad (25)$$

Where,

I_{a2}= annual increment of woody biomass in second term (Mg FM ha^{-1} yr^{-1})

FM_{Age}= total fresh matter weight at a specific age (Mg FM ha^{-1})

Δt = the amount of time expired between t = 1 and t = 2 (years)

FM_{ap}= annual cuttings/annually pruned wood (Mg ha^{-1} yr^{-1})

Foliage and fruits

To calculate the C-flux in foliage, we used data on the AGB-share of foliage of He et al. (2018); Nilsson and Schopfhauser (1995); H. Zhang et al. (2017) and Borden et al. (2014) (Appendix B.2; *Table 46*).

Herbs and grasses

Our data on grass production was based at data of (Oosterbaan, van Blitterswijk, Holshof, & de Jong, 2008) and the land user (Table 122).

Table 12 Grass production at various grassland parcels.

Parcel	Management (Appendix A.5)	Grass production (Mg C ha^{-1} yr^{-1})	Source
GrNE	Fertilised	4.343	Land user (Mr. Brus)
C2011, C1995, C1993, J1976, J1966, J1895, GrS	Unfertilised	1.520	Oosterbaan et al. (2008, p. 26); grassland codes 3c and 3d (these values are confirmed as reasonable by the owner of the orchard)

Compost

The C-flux originating form compost was calculated by multiplying FM with the share of DM resp. OM and carbon:

$$Cflux_{compost} = FM_{compost} * f_{FM-DM} * f_{DM-OM} * f_{OM-C} \quad (26)$$

Where,

$Cflux_{Compost}$ = annually applied mass of carbon in compost (Mg C ha^{-1} yr^{-1})

FM_{Comp} = annually applied fresh matter mass of compost (Mg FM ha^{-1} yr^{-1})

f_{FM-DM} = share of dry matter in fresh matter = 0.599 (CDM, 2017)

f_{DM-OM} = share of organic matter in dry matter = 0.404 (a mix of CDM, 2017)

f_{OM-C} = share of carbon in organic matter = 0.45 (CDM, 2017)

4.4 External carbon

4.4.1 External C-flux

Manure and lime

To calculate the C-stock in fresh manure, we used a variation of equation 26, based on values of CDM (2017). Manure contains a type of carbon that is very unstable and largely exposed to microbial respiration. Therefore, we calculated with the amount of C in manure that remains in the soil after 1 year. We multiplied the original amount of C in manure with a humification factor of 0.45 (CDM, 2017), to calculate the amount of C in manure that remains after 1 year.

The amount of C in the applied lime (mostly $CaCO_3$) was calculated with the help of the relative atomic mass.

4.5 Total C-flux

The total C-flux is the sum of C-fluxes in SOC, BGB and AGB (all values compared to C-stock at control parcel):

$$Cflux_{Total} = Cflux_{SOC} + SOCflux_{BGB} + SOCflux_{AGB} \quad (27)$$

Where,

$Cflux_{Total}$ = flux of carbon at a parcel (Mg C ha^{-1} yr^{-1})

$Cflux_{SOC}$ = SOC flux at a parcel (Mg C ha^{-1} yr^{-1})

$Cflux_{BGB}$ = BGB flux of carbon at a parcel (Mg C ha^{-1} yr^{-1})

$Cflux_{AGB}$ = AGB flux of carbon at a parcel (Mg C ha^{-1} yr^{-1})

The control parcels also have an autonomous C-flux. The gross -or baseline- C-flux is the sum of total the C-flux and C-flux in the control parcel:

$$Cflux_{Baseline} = Cflux_{Total} + Cflux_{Control} \quad (28)$$

Where,

$Cflux_{Baseline}$ = gross flux of carbon at a parcel, compared to status quo C-stock (Mg C ha^{-1} yr^{-1})

$Cflux_{Total}$ = flux of carbon at a parcel, compared to C-stock at control parcel (Mg C ha^{-1} yr^{-1})

$Cflux_{Control}$ = autonomous C-flux at a control parcel (Mg C ha^{-1} yr^{-1})

The C-fluxes at our control parcels might be larger than just the SOC-flux, though for both grassland and cropland we considered the biomass-flux out to be zero, because these fluxes are quite variable at a small-time scale and close to zero at a long-time scale.

To calculate the balance of all C-fluxes, the following equation was applied:

$$Cflux_{Bal} = Cflux_{Baseline} - (Cflux_{Compost} + Cflux_{Crop} + Cflux_{Manure} + Cflux_{Lime}) \quad (29)$$

Where:

$Cflux_{Bal}$ = balance of all fluxes; photosynthesis – respiration (Mg C ha^{-1} yr^{-1})

$Cflux_{Baseline}$ = gross flux of carbon at a parcel, compared to status quo C-stock (Mg C ha^{-1} yr^{-1})

$Cflux_{Compost}$ = annually applied compost at a parcel (Mg C ha^{-1} yr^{-1})

$Cflux_{Crop}$ = annual crop left at a parcel (Mg C ha^{-1} yr^{-1})

$Cflux_{Manure}$ = annually applied manure at a parcel (Mg C ha^{-1} yr^{-1})

$Cflux_{Lime}$ = annually applied lime at a parcel (Mg C ha^{-1} yr^{-1})

4.6 Model

To predict future pathways of C-sequestration in nut orchards at a comparable soil we developed a process-oriented empirical model (FAO, 2019b). The model called Carbon Assessment for Nut Orchard Environment Model (CANOE) was built with the help of Stella software (for layout see Appendix B.3; Figure 15).

Table 13 CANOE model parameters.

Parameter	**Definition**	**Unit**
Orchard age	Orchard age	Years
Ccontr conc	C-concentration at a depth of 0-30 cm or 30-60 cm at a control parcel	%
Cparcel conc	C-concentration at a depth of 0-30 cm or 30-60 cm at a specific nut orchard	%
Soil density	Soil bulk density	Mg Mg^{-1}
New grass cover	The amount of soil covered by grass (added compared to control parcel)	%
Ia BGB *Juglans*	Annual increment of Belowground Biomass in *Juglans* orchards	Mg C ha^{-1} yr^{-1}
Ia BGB *Corylus*	Annual increment of Belowground Biomass in *Corylus* orchards	Mg C ha^{-1} yr^{-1}
Ia AGB *Juglans*	Annual increment of Aboveground Biomass in *Juglans* orchards	Mg C ha^{-1} yr^{-1}
Ia AGB *Corylus*	Annual harvest of Aboveground Biomass in *Corylus* orchards (pruning & thinning)	Mg C ha^{-1} yr^{-1}
Ia AGB-harv *Juglans*	Annual harvest of Aboveground Biomass in *Juglans* orchards (pruning & thinning)	Mg C ha^{-1} yr^{-1}
Ia AGB-harv *Corylus*	Annual increment of Aboveground Biomass in *Corylus* orchards	Mg C ha^{-1} yr^{-1}
Soil type	Type of soil beneath the orchard, Zn23=101, Hn23=102, Hn21(sandy soil)=103	Code
If *Juglans*, then=1	A parameter to help the model choose between *Juglans/Corylus*	Dimensionless
If *Corylus*, then=1	A parameter to help the model choose between *Juglans/Corylus*	Dimensionless
Fruits *Juglans*	Annual harvest of fruits from *Juglans* orchards	Mg C ha^{-1} yr^{-1}
Fruits *Corylus*	Annual harvest of fruits from *Corylus* orchards	Mg C ha^{-1} yr^{-1}
Soil volume	The volume of a 30 cm thick layer of soil at 1 ha	m^3

The model is based on stocks and fluxes as visualised in our conceptual model (Figure 6) and can be adjusted by a set of 17 parameters (Table 13) and has multiple stocks as output (Table 14).

Table 14 CANOE model components.

Component	Definition	Type	Unit
SOC	Net flux of SOC (compared to control parcel)	Flux	Mg C ha^{-1} yr^{-1}
BGBloss	Flux of belowground biomass in grass that is lost	Flux	Mg C ha^{-1} yr^{-1}
BGBgrass	Flux of belowground biomass in grass	Flux	Mg C ha^{-1} yr^{-1}
BGBtrees	Flux of belowground biomass in trees	Flux	Mg C ha^{-1} yr^{-1}
AGBloss	Flux of aboveground biomass in grass that is lost	Flux	Mg C ha^{-1} yr^{-1}
AGBgrass	Flux of aboveground biomass in grass	Flux	Mg C ha^{-1} yr^{-1}
AGBtrees	Flux of aboveground biomass in trees	Flux	Mg C ha^{-1} yr^{-1}
AGBharvest	Flux of woody biomass out of the orchard (harvested)	Flux	Mg C ha^{-1} yr^{-1}
Fruits-harvest	Annual harvest of fruits	Flux	Mg C ha^{-1} yr^{-1}
Totalflux	Total flux of carbon at the orchard, compared to the control parcel (harvested wood included)	Flux	Mg C ha^{-1} yr^{-1}
ΔSOCstock	Additional SOC stock in orchard of study compared to control parcel	Stock	Mg C ha^{-1}
Cstock BGB grass	C-stock of belowground biomass in grass	Stock	Mg C ha^{-1}
Cstock BGB trees	C-stock of belowground biomass in trees	Stock	Mg C ha^{-1}
Cstock AGB grass	C-stock of aboveground biomass in grass	Stock	Mg C ha^{-1}
Cstock AGB trees	C-stock of aboveground biomass in trees (harvested wood included)	Stock	Mg C ha^{-1}
Cstock total ass	Total C-stock of all belowground and aboveground biomass (harvested wood included)	Stock	Mg C ha^{-1}
Cstock AGB harvest	C-stock of all harvested wood	Stock	Mg C ha^{-1}
Cstock Fruits	C-stock of all harvested fruits	Stock	Mg C ha^{-1}

4.7 Statistical analysis

Not all parcels have a homogeneous vegetation structure, so we had to make a stratification. All sampling was based on the method of stratified selective sampling, as elaborated by Echnoserve PLC (2014); FAO (2019a) and Groennou (1984). According to the recommendations of FAO (2019a) for soil sampling, we applied the method of composite samples. All of our samples taken in the 0-30 cm zone were composed of about 40 cores. Samples in the 30-60 cm zone were composed of 2 cores. FAO-recommends, to do a pre-sampling and to take at least three composite samples per stratum, could not be taken into account, because we took only one, and sometimes two composite samples per stratum. Information about the systematic random choice of sampling locations and additional information can be found in Appendix B.1.

To prevent that certain samples from specific strata would be overrepresented, it was necessary to determine a weighted mean. To calculate the weighted mean of soil samples, the following equation was applied (StackExchange, 2014):

$$\mu_w = \frac{\sum_{i=1}^{n} x_i \, w_i}{\sum_{i=1}^{n} w_i} \qquad (30)$$

Where,

μ_w = weighted mean

w = weight

n = number of weights

x = value

To calculate the weighted variance the following equation was applied (StackExchange, 2014):

$$s_w{}^2 = \frac{\sum_{i=1}^{n} w_i}{\left(\sum_{i=1}^{n} w_i\right)^2 - \sum_{i=1}^{n} w_i^2} \cdot \sum_{i=1}^{n} (x_i - \mu_w)^2 \qquad (31)$$

Where,

$s_w{}^2$ = variance

μ_w = weighted mean

w = weight

n = number of values

i = interval

x = value

To calculate the weighted standard error (SE) the following equation was applied (StackExchange, 2014):

$$SE = \sqrt{\frac{s_w{}^2}{n}} \qquad (32)$$

Where,

SE = standard error

$s_w{}^2$ = variance

n = number of values

To calculate the SE of two or more added variables the following equation was applied (Hogan, 2006), which was adjusted for multiplication and division of variables:

$$\Delta a = \sqrt{(\Delta b)^2 + (\Delta c)^2} \qquad (33)$$

Where,

a = combined variable

b = variable 1

c = variable 2

SE-calculations were made for four different parameter groups: soil: soil data analysed in laboratory and sampled at multiple locations at a parcel, all other soil data, non-soil parameters and combinations of parameters. Each group required a specific SE calculation (Table 15).

Table 15 Standard error calculation for different parameter groups.

Parameter group	Number of samples/stratum (n)	Standard error calculation
Soil data analysed in laboratory, SOM & SOC	2 or more	Equation 30 & 31; laboratory error can be neglected; 0.1% for SOC and 0.5% for SOM
Other soil data	1 (n=1)	Not possible
All other non-soil parameters	In most cases one of the parameters is based on a single sample (n=1)	Guessed by author (based on 95% interval and limited number of samples)
Combinations of parameters	irrelevant	Equation 32

4.8 Sensitivity analysis

A sensitivity analysis shows how sensitive results are to the change by adjusting a specific parameter. We elaborated a sensitivity analysis on the next three parameters:

1. SOC stock to changes in soil bulk density, since soil bulk density has a large influence on C-stock calculations and bulk density results have a large range;
2. C-stock to changes in soil A-horizon depths, since carbon concentrations might have a strong relation to the depth of the A-horizon. All of our parcels have a history of agricultural use. In agricultural soil a plow pan can often be found at a depth of 30 cm, with a well-mixed soil above it and a more or less undisturbed soil beneath it. This plow pan often matches with the boundary between the A- and the B-horizon. In general, most carbon can be found in the top 30 cm of the soil. Our sampling method was based on collecting samples either in the 0-30 or the 30-60 cm zone (Appendix B.1). It is likely though, that if the A-horizon stretches a few cm below this 30 cm, that this soil will have the same percentage of C as the rest of the A-horizon in the top 30 cm of soil. We therefore made a sensitivity analysis of the change C-stocks as a result of a different soil depth classification;
3. SOC flux to former land use of control parcels, since former land use management might have a large effect on the complex task of composing chronosequences. The chronosequences were compiled by combining characteristics of the soil (Table 3 & Appendix C.3) and historic and current land use management (Appendix A.5; Table 43) into four groups of parcels (Table 4). Compiling chronosequences always requires that details (e.g. on land use management) are generalised. In our study area land use management has not been uniform for the whole area and has been different from parcel to parcel over the past decades. Therefore, the question is: how large is the influence of former land use management on chronosequence based SOC-fluxes?

The sensitivity is based on the normalised change in input and output (Haefner, 2005):

$$S = \left(\frac{Out_i - Out_o}{Out_o} \right) / \left(\frac{P_i - P_o}{P_o} \right) \qquad (34)$$

Where,

S = Sensitivity (dimensionless)

P_o = Original parameter

P_i = Parameter of choice

Out_o = Model output with original parameter

Out_i = Model output with parameter choice i

5 Results

This chapter presents the results of our data collection and analysis. Additional results can be found in Appendices C.3, C.4 and C.5.

5.1 SIC

The SIC stock was derived from the soil samples and ranges from 0.07 % to 0.04 % (Table 16).

Table 16 Soil Inorganic Carbon contents of the soil of various parcels.

Parcel			Ar	C2011	C1993	GrS	J1895	GrNE	J1976	J1966	C1995
Category	Unit	Soil depth (cm)	C-loamy hydro	C-loamy hydro	C-loamy hydro	J-sandy	J-sandy	C-loamy brown + J-loamy	J-loamy	J-loamy	C-loamy brown
C-inorganic	%	0-30	0.07	0.06	0.06	0.06	0.06	0.04	0.05	0.06	0.05

The SIC stock is relatively small and stable, so this parameter is not further elaborated.

5.2 SOC

5.2.1 SOC stock

SOC stocks at our parcels range from 252.4 Mg ha^{-1} (J1895) to 71.3 Mg ha^{-1} (C2011) (0-60cm depth, Table 17). SOC stock calculations are based on C-concentrations in different soil layers (Eq. 3). Looking at the C-concentration in different soil layers at the level of parcels (Table 17) we see the highest concentrations in the 0-30cm layer. Within this 0-30cm layer the highest concentration (3.8%) was found in the J1895 parcel and the lowest in the Ar parcel. At a depth of 30-60 cm the highest concentration (2.8%) was also found in the J1895 parcel and the lowest concentration -0.4%- was found in C2011 (Table 17).

At the spatial level we see that SOC concentrations in the top 0-30cm layer of different strata ranges from 2.7% to 1.4% at *Corylus* parcels and from 4.5% to 2.3% at *Juglans* parcels (Table 18 and Figure 77A). The highest concentrations were found in the S1 and S3 strata (row with bare soil covered by trees and the row formerly covered by trees) and the lowest values in the S2 stratum (row always covered by grass and without trees). The concentrations in the C2011 and C1995 parcels are almost equal.

Within the two parcels with the youngest *Juglans* trees (J1976 and J1966), the concentration does not diverge much between the different strata (S1.5, S3.0, S4.5 and S6.0). Within the parcel with the oldest Juglans tree (J1895) the concentration is lower in strata further away from the centre of the tree (Figure 7B).

When we display all chronosequences as different bullets with the same colour (Figure 8 SOC stock (Mg C ha-1) for four different chronosequences (A: Corylus, B: Juglans).Figure 8) we see that all SOC values increase with time, except for C2011 which has a slightly lower SOC stock then the control parcel (Ar) (Table 17). The strongest increase was observed in the C-loamy brown (*Corylus*) chronosequence. The lowest increase can be observed in the C-loamy hydro and the J-sandy chronosequence.

Table 17 SOC concentrations and SOC stock at 0-30 and 30-60cm depth (All values for 0-30 cm depth are based on replica samples; composed by mixing 40 cores (additional information: Appendix B.1). All values for 30-60 cm depth are composed by mixing two cores. Values for Ar at a depth of 0-30 cm are the mean of data from A1 and A2 (Appendix C.1), values for 30-60 cm depth are based on A1. Values for C2011 are collected at C20 C2011-S1, except C and OS, which are the mean of samples C2011-S1, -S2 and -S3. Values for C1993 are collected at C1993-S1, except C and OS, which are the mean of samples C1993-S1, -S2 and -S3).

			Ar	C2011	C1993	GrS	J1895	GrNE	J1976	J1966	C1995
Category	Unit	Soil depth (cm)	C-loamy hydro	C-loamy hydro	C-loamy hydro	J-sandy	J-sandy	C-loamy brown + J-loamy	J-loamy	J-loamy	C-loamy brown
SOC	%	0-30	1.4	1.5	1.5	3.5	3.8	1.8	2.4	2.6	2.4
SOC	%	30-60	0.5	0.4	0.6	2.0	2.8	0.4	0.7	1.7	1.1
Soil bulk density	g/L	0-30	1267	1267	1267	1267	1267	1267	1267	1267	1267
SOC stock	Mg ha^{-1}	0-30	53.2	56.1	58.0	133.1	145.9	68.4	91.7	97.3	92.7
SOC stock	Mg ha^{-1}	30-60	19.0	15.2	22.8	76.0	106.4	15.2	26.6	64.6	41.8
SOC stock	Mg ha^{-1}	0-60	72.2	71.3	80.8	209.1	252.4	83.6	118.3	161.9	134.5

Table 18 SOC concentration in strata of parcels with trees (0-30 cm depth, All values are based on replica samples; composed by mixing 40 cores. Additional information: Appendix B.1).

		C2011	C1995	C1993	J1895	J1966	J1976
Stratum	Unit	Corylus	Corylus	Corylus	Juglans	Juglans	Juglans
S1 (tree row)	mass-%	1.50	1.70	2.65			
S2 (alley)	mass-%	1.40	1.40	2.20			
S3 (former tree row)	mass-%	1.60	1.60	2.70			
S1.5	mass-%				4.50	2.30	2.60
S3.0	mass-%				3.40	2.40	2.50
S4.5	mass-%				4.20	2.40	2.60
S6.0	mass-%				3.60	2.60	2.50

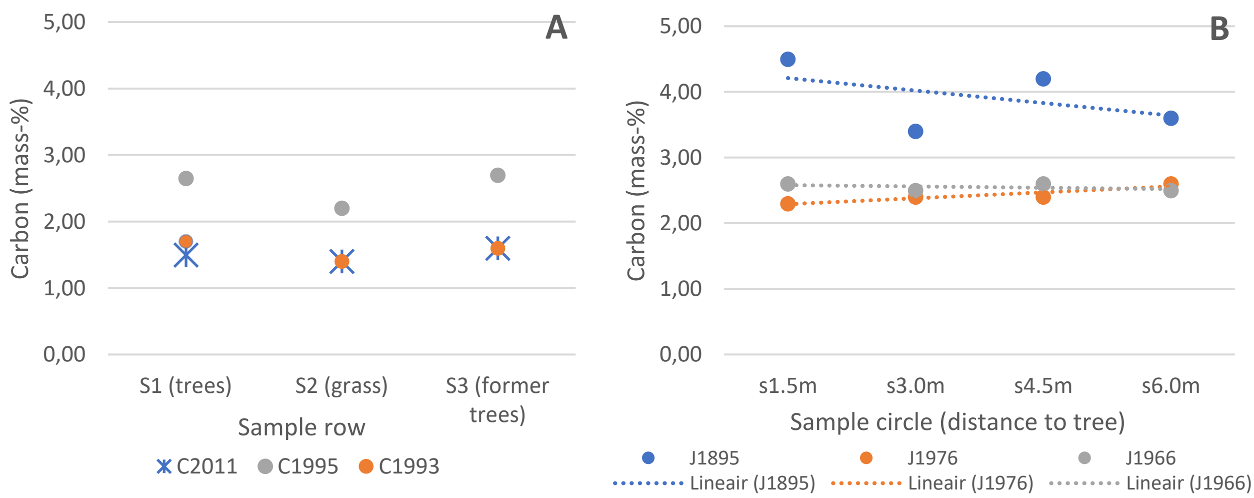

Figure 7 SOC concentration (mass % from soil) variation within parcels (A = Corylus, B = Juglans).

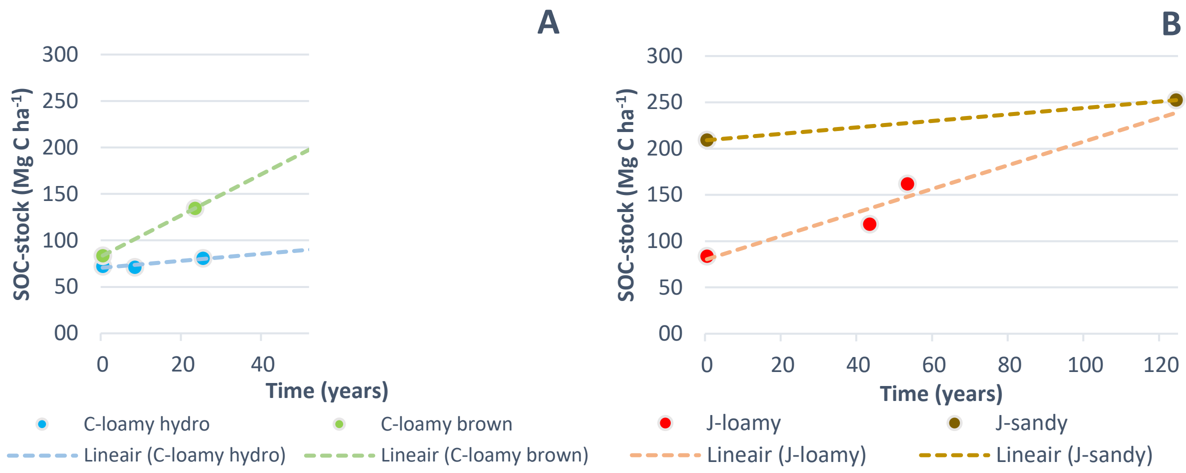

Figure 8 SOC stock (Mg C ha-1) for four different chronosequences (A: Corylus, B: Juglans).

Interpretation of results

In general, the SOC concentration shows a large spatial variety within the parcels and even larger spatial variety between the different parcels. This means that SOC stocks can differ to a great extend over short distances and are vulnerable to changes in vegetation cover and land use management. All but one parcels (C2011) have a larger SOC stock than their control parcel. SOC concentrations and SOC stocks are within the range of values found by Cardinael et al. (2017) for various locations in France. The C2011 parcel has been covered by trees for just 8 years. To detect a decrease in C-concentration in the first years after planting is in line with Paul et al. (2002). The current values we found for the GrNE parcel (3.7% SOM) is close to the range of 2.6 to 3.6% as found by Van Eekeren and Zaneveld-Reijnders (2011). The current SOM level we found for the GrS parcel is much higher (6.4% SOM).

When we look at the angle of the linear trend (Figure 8), we see three remarkable values: the C-loamy brown line is very steep, the J-loamy increases strongly after the year 43 (t = 43) and the J-sandy line is relatively flat. For C-loamy brown this might be explained by the fact that the land use management history before planting of the C1995 parcel is not as comparable to the land use management history of the control parcel as expected. For the J-loamy chronosequence the explanation might be that the J1966 parcel is of another quality than the other two parcels. When we leave C-loamy hydro chronosequences out of consideration and we remove the J1966-point from the J-loamy chronosequence, then the angle of the J-sandy chronosequence is not that different from all other values.

5.2.2 SOC flux

The mean annual SOC flux is 0.84 Mg SOC ha^{-1} yr^{-1} for the top 60 cm of the soil. The flux in the 0-30 cm depth layer is 0.46 Mg SOC ha^{-1} and in the 30-60 cm layer is 0.37 Mg SOC ha^{-1} yr^{-1}. The SOC accumulation rates at 0-30 cm depth for the different parcels range from 1.03 to 0.10 Mg SOC ha^{-1} yr^{-1} (Table 19, Figure 9). For the 30-60 cm depth layer it ranges from 1.13 to –/–0.48 Mg SOC ha^{-1} yr^{-1}. For both depths the highest value was found at the C1995 parcel.

Table 19 SOC flux in nut tree parcels compared to their control parcel (All values for 0-30 cm depth are based on replica samples; composed by mixing 40 cores (additional information: Appendix B.1). All values for 30-60 cm depth are composed by mixing two cores. SE = standard error).

			C2011	C1993	J1895	J1976	J1966	C1995	Mean
Category	Unit	Soil depth (cm)	C-loamy hydro	C-loamy hydro	J-sandy	J-loamy	J-loamy	C-loamy brown	All (SE)
SOC flux	Mg ha^{-1} yr^{-1}	0-30	0.36	0.19	0.10	0.54	0.54	1.03	0.46 ± 0.01
SOC flux	Mg ha^{-1} yr^{-1}	30-60	-0.48	0.15	0.25	0.27	0.93	1.13	0.37 ± 0.05
SOC flux	Mg ha^{-1} yr^{-1}	0-60	-0.12	0.34	0.35	0.81	1.48	2.16	0.84 ± 0.26

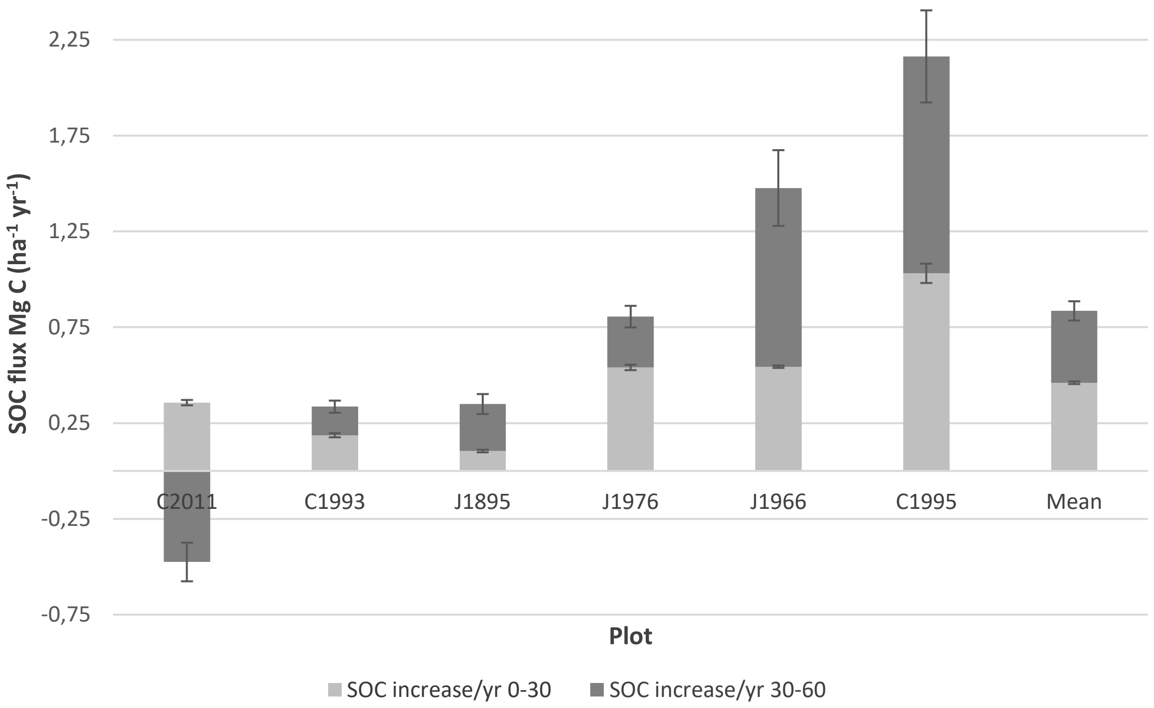

Figure 9 SOC flux (Mg C ha-1 yr-1) for all nut tree parcels.

Interpretation of results

Our mean SOC sequestration rates are largely in line with the results of Cardinael et al. (2017), Pardon et al. (2017) and Wotherspoon et al. (2014) (Table 2). The mean SOC sequestration rate they found is smaller than ours, though our study ranges to 60 cm beneath the surface and theirs to 23, 30 resp. 40 cm.

5.3 Biomass

5.3.1 Biomass C-stock

In forests fallen leaves and branches form a litter layer. At the nut orchard all leaves and other organic litter is removed, so for most of the time a litter layer is absent at the orchard. All other biomass C-stocks that we distinguished (Figure 6) are elaborated in the next paragraphs. At the level of our parcels C1995, and to a lesser extent J1966, seem to have a remarkably high C-sequestration rate.

Wood C-stock

The mean C-stock currently stored in wood is 23 Mg C ha^{-1} (harvested wood excluded). The highest amount (75.3 Mg C ha^{-1}) was found in the parcel with the oldest tree (J1895) and the lowest amount in the parcel with the youngest trees (C2011; 2.3 Mg C ha^{-1}) (Table 20). This means that wood is another important stock of carbon at the orchard (Figure 10). The amount of carbon in wood is not as large as the SOC-stock. Most of the wood produced by *Juglans* trees is still present, because only some branches have been removed to improve the shape (pruning). This is not the case for the *Corylus* trees.

Table 20 C-stock in wood of trees (C-stocks of both the *Corylus*-chronosequences have been complemented with C-stocks from the years 11, 13, 18 and 21 which were composed by calculations based on historic management data. Additional data on mean tree diameter, height and number of stems per hectare can be found in Table 53).

			Time (years)										
Chronosequence	**C-wood**	**Unit**	**0**	**8**	**11**	**13**	**18**	**21**	**23.5**	**25.5**	**43**	**53**	**124**
C-loamy hydro	current	Mg C ha^{-1}	0.0	2.3		2.9		6.7		8.4			
	harvested	Mg C ha^{-1}	0.0	1.4		3.1		15.6		18.5			
C-loamy brown	current	Mg C ha^{-1}	0.0		2.9		8.9		11.6				
	harvested	Mg C ha^{-1}	0.0		4.8		14.9		15.9				
J-loamy	current	Mg C ha^{-1}	0.0								27.7	13.6	
	harvested	Mg C ha^{-1}	0.0								0.7	0.3	
J-sandy	current	Mg C ha^{-1}	0.0										75.3
	harvested	Mg C ha^{-1}	0.0										7.5

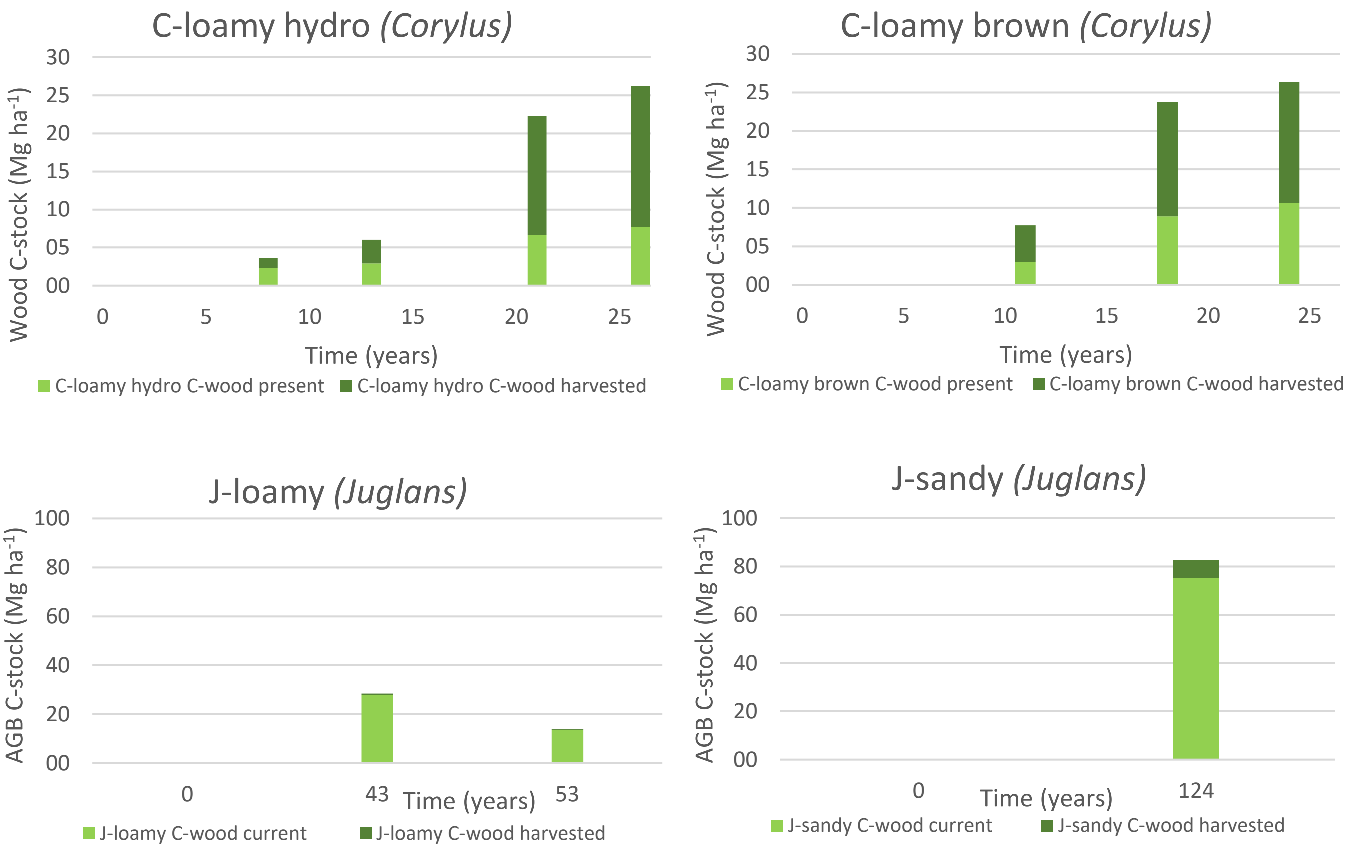

Figure 10 C-stock in woody aboveground biomass (foliage, branches and stems) in living trees, respectively harvested trees (in Mg C ha-1) at various times (the varying width of the columns has no meaning).

Of all trees originally planted, less than one quarter remains in the C1993 and C1995 parcel as a result of two thinnings (Appendix A.5). A small part of the removed or harvested trees has returned to the orchard as compost, but most of the wood has been used for heating.

Interpretation of results

The wood C-stock at *Juglans* parcels is much larger than the wood C-stock at *Corylus* parcels. It is remarkable to see that the wood C-stock in the J-loamy chronosequence drops from t = 43 to t = 53. Three variables might have been of large influence on this drop: 1. J1966 and J1976 both are based on a single tree, so reliability of the outcome is limited, 2. J1976 is supposed to be a faster growing variety than J1966 and 3. J1976 was already 5 years old when it was planted at this location.

In general our results are largely in line with the results of Cardinael et al. (2017); Wotherspoon et al. (2014) which range from 0.017 to 36.69 Mg C ha^{-1}. Our results for J1895 are much higher, albeit this can be explained by the fact that all trees in the study of Cardinael et al. (2017) are much younger, and tree age and wood volume have a strong positive relation. Palma et al. (2007) also found a stock, 179 Mg C ha^{-1}, that far exceeds our findings. It is likely that the amount of carbon stored in wood will differ between studies, because these values are largely dependent on parameters like tree species, tree density, soil quality, micro-climate and age, which occur in different combinations in studies.

The C-stock in wood per hectare at the two *Corylus* chronosequences (C-loamy hydro and C-loamy brown) seems to have grown relatively fast between t = 13 and t = 21 (C-loamy hydro) and t = 11 and t = 18 (C-loamy brown). This is not in line with Dold et al. (2019) who found a maximum growth of the stock at an age of 11 years, though this number relates to other tree species (Oak and Pecan) than the ones we studied. Different stock growth over time is explainable, because each tree species has its own growth characteristics and our C-stocks have been largely influenced by stem number reductions.

Herbs and grasses C-stock

The C-stock in herbs and grasses is estimated at 1.26 to 0.61 Mg C ha^{-1} (Table 21) (calculations Ch. 4.5).

Table 21 C-stock in AGB of herbs and grasses.

Parcel		Ar	C2011	C1993	GrS	J1895	GrNE	J1976	J1966	C1995
Category	Unit	C-loamy hydro	C-loamy hydro	C-loamy hydro	J-sandy	J-sandy	C-loamy brown + J-loamy	J-loamy	J-loamy	C-loamy brown
AGB-grasss	Mg C/ha	0	0.61	0.76	0.77	0.77	1.26	0.77	0.77	0.77

Belowground biomass C-stock

The belowground biomass C-stock (coarse and fine roots) ranges from 21.4 Mg C ha^{-1} at the J1895 parcel to 0.3 Mg C ha^{-1} for the cropland (Table 22, Figure 11). The general picture is: 'The longer covered under trees, the higher the BGB C-stock'.

Table 22 C-stock in BGB of trees, herbs and grasses.

Parcel		Ar	C2011	C1993	GrS	J1895	GrNE	J1976	J1966	C1995
Category	Unit	C-loamy hydro	C-loamy hydro	C-loamy hydro	J-sandy	J-sandy	C-loamy brown + J-loamy	J-loamy	J-loamy	C-loamy brown
BGB-trees	Mg C/ha	0	0.7	2.5	0	17.8	0	6.8	3.4	3.3
BGB-herbs & grasses	Mg C/ha	0.3	2.8	3.5	3.6	3.6	5.9	3.6	3.6	3.6
BGB-total	Mg C/ha	0.3	3.5	6.0	3.6	21.4	5.9	10.4	7.0	6.9

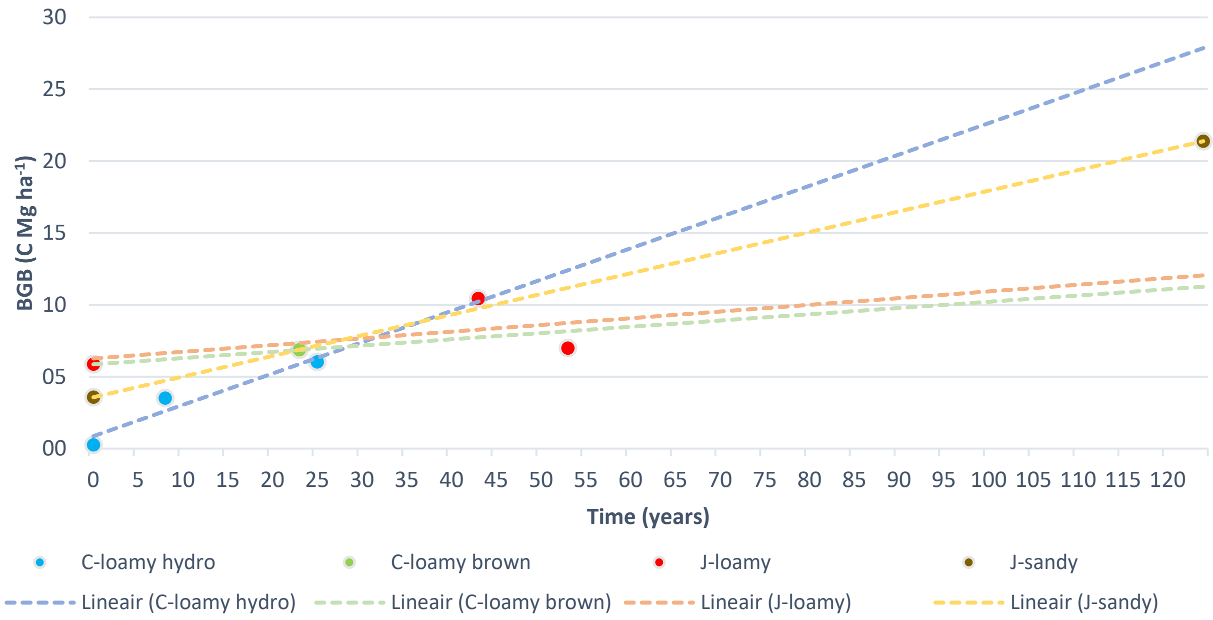

Figure 11 C-stock in belowground biomass (roots) in living trees, herbs and grasses (in Mg C ha-1 yr-1).

Interpretation of results

The BGB of *Corylus* tree roots is probably a lot higher than calculated in Table 22, since BGB is based upon the living trees; however 50% of the trees has been cut in the past decades. Only the AGB of these trees has been removed. The core of these roots has been chopped and was mixed with the soil and the rest of the roots was left undisturbed (and left out of sampling; Appendix B.1). It is likely that most of these roots are still slowly decomposing in the ground and adding to SOC levels. This is also an explanation for the slow growth of BGB in de C-loamy hydro chronosequence after $t = 8$. All BGB values are likely to have a large error nonetheless, because Nair (2012) questions the use of allometric equations, by stating that tree growth and root biomass have no direct relation.

5.3.2 Biomass C-flux

Wood C-flux

The mean C-flux in wood is 0.71 Mg C ha^{-1} yr^{-1}. C-fluxes range from 1.13 Mg ha^{-1} yr^{-1} for the C1995 parcel to 0.24 Mg C ha^{-1} yr^{-1} for the J1966 parcel (Table 23).

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Table 23 AGB-wood C-flux in nut tree parcels (based on current wood stock and harvested wood).

		C2011	C1993	J1895	J1976	J1966	C1995	Mean
Category	Unit	C-loamy hydro	C-loamy hydro	J-sandy	J-loamy	J-loamy	C-loamy brown	
AGB-wood C flux	Mg C ha^{-1} yr^{-1}	0.46	1.06	0.67	0.66	0.26	1.17	0.71 ± 0.03

Interpretation of results

Our C-sequestration rates for wood are in line with Cardinael et al. (2017) and Wotherspoon et al. (2014), larger than the findings of Dold et al. (2019), though smaller than the findings described by Palma et al. (2007) and Thevathasan and Gordon (2004). Differences in sequestration rates are likely to be explained by parameters like tree species, tree density, soil quality, micro-climate and age.

Herbs and grasses C-flux

The mean AGB C-flux in herbs and grasses is 0.01 Mg C ha^{-1} yr^{-1}. C-fluxes range from 0.076 Mg ha^{-1} yr^{-1} for the C2011 parcel to -/-0.20 Mg C ha^{-1} yr^{-1} for the C1995 parcel (Table 24).

Table 24 C-flux in herbs and grasses (compared to their control parcel).

Parcel		C2011	C1993	J1895	J1976	J1966	C1995	Mean
Category	Unit	C-loamy hydro	C-loamy hydro	J-sandy	J-loamy	J-loamy	C-loamy brown	
Herbs and grasses	Mg C ha^{-1} yr^{-1}	0.076	0.030	0	-0.011	-0.009	-0.020	0.011 ± 0.004

Belowground biomass C-flux

The mean C-flux in BGB is 0.158 Mg C ha^{-1} yr^{-1}. C-fluxes range from 0.408 Mg ha^{-1} yr^{-1} for the C2011 parcel to 0.021 Mg C ha^{-1} yr^{-1} for the J1966 parcel (Table 25).

Table 25 C-flux in BGB of trees, herbs and grasses (compared to their control parcel).

Parcel		C2011	C1993	J1895	J1976	J1966	C1995	Mean
Category	Unit	C-loamy hydro	C-loamy hydro	J-sandy	J-loamy	J-loamy	C-loamy brown	
BGB-trees	Mg C ha^{-1} yr^{-1}	0.086	0.097	0.144	0.160	0.064	0.138	0.115 ± 0.050
BGB-herbs & grasses	Mg C ha^{-1} yr^{-1}	0.322	0.129	0	-0.053	-0.043	-0.096	0.043 ± 0.020
BGB-total	Mg C ha^{-1} yr^{-1}	0.408	0.226	0.144	0.106	0.021	0.043	0.158 ± 0.050

Foliage and fruits C-flux

The mean C-flux in foliage and fruits is 2.64 Mg C ha^{-1} yr^{-1}. C-fluxes range from 7.20 Mg ha^{-1} yr^{-1} for the J1895 parcel to 0.945 Mg C ha^{-1} yr^{-1} for the C2011 parcel (Table 26).

Table 26 C-flux in foliage and fruits of nut trees.

		C2011	C1993	J1895	J1976	J1966	C1995	Mean
Category	Unit	C-loamy hydro	C-loamy hydro	J-sandy	J-loamy	J-loamy	C-loamy brown	
Foliage production	Mg C ha^{-1} yr^{-1}	0.216	0.727	6.051	2.228	1.097	0.998	1.886 ± 0.569
Fruits production	Mg C ha^{-1} yr^{-1}	0.729	0.729	1.144	0.664	0.511	0.729	0.751 ± 0.082
Total	Mg C ha^{-1} yr^{-1}	0.945	1.456	7.195	2.892	1.607	1.727	2.637 ± 0.573

Interpretation of results
The amount of foliage for J1895 is large compared to the other trees. Maybe the allometric equation, at which our calculations were based, is not suitable and overestimates for old trees.

Compost C-flux

The amount of carbon added to the orchard in the form of compost is 0.13 Mg C ha^{-1} yr^{-1}. The input to the compost comes from foliage, grass cuttings, prunings, fruit shells and decried fruits (Table 27). Half of annual prunings are burned, the rest is added to the compost (Appendix A.5). From all grass cuttings, also half is added to the compost heap, the rest is left on top of the gras.

Table 27 Mass balance for compost (DM=dry matter).

In				Out		
	Mg DM ha^{-1} yr^{-1}	Mg C ha^{-1} yr^{-1}			Mg DM ha^{-1} yr^{-1}	Mg C ha^{-1} yr^{-1}
Foliage	5.598	2.601		Compost (after 1yr)	0.799	0.131
Grass cuttings	1.167	0.507		Humification loss	6.570	3.271
Prunings	0.176	0.085				
Fruits, shells	0.357	0.174				
Fruits decried	0.071	0.035				
Sum	7.369	3.401			7.369	3.401

Based on DM, the humification rate (output divided by input) from fresh matter to stable compost over a period of three years is 0.11. Three years is the mean staying time when emptying the compost heap after six years. Based on C-mass the humification rate from fresh matter to stable compost over a period of three years is 0.04.

According to CDM (2017) one year after applying the compost on the land, 10% of C in compost will have been lost to the air by humification processes (respiration).

5.4 External carbon

The carbon stocks and fluxes at our study area are no closed systems but are part of a global system. In this paragraph we will discuss sources of carbon which are actually brought in our system externally, i.e. in the form of manure and lime.

Manure and lime
The amount of carbon in manure that is applied in the *Corylus* parcels is 0.38 Mg C ha^{-1} yr^{-1}, with an exception for parcel C2011, where 0.58 Mg C ha^{-1} yr^{-1} is being added, because in the first 18 years a larger amount of manure is added. The largest amount of manure is applied at the Ar-parcel (1.278 Mg ha^{-1} yr^{-1}), because at the parcels GrS, J1895, J1966 and J1976 no manure is applied at all (Table 28). From CDM (2017) we learn that in general within one year 55% of carbon in manure is humified and lost into air by respiration. Maillard and Anters (2014) in FAO (2019a) found on the base of a meta-analysis that the long term capacity of soil to capture carbon from added manure is 15%.

The amount of carbon that is brought in as a part of lime is very small compared to other C-fluxes.

Table 28 C-flux in manure and chalk.

Parcel		Ar	C2011	C1993	GrS	J1895	GrNE	J1976	J1966	C1995
Category	Unit	C-loamy hydro	C-loamy hydro	C-loamy hydro	J-sandy	J-sandy	C-loamy brown + J-loamy	J-loamy	J-loamy	C-loamy brown
C in manure	Mg C ha^{-1} yr^{-1}	1.278	0.575	0.383	0.000	0.000	2.237	0.000	0.000	0.383
Remaining C from manure after 1 year	Mg C ha^{-1} yr^{-1}	0.575	0.259	0.173	0.000	0.000	1.006	0.000	0.000	0.173
Lime	Mg C ha^{-1} yr^{-1}	0.048	0.009	0.009	0.009	0.009	0.048	0.009	0.009	0.009

5.5 Total C-stock

The total C-stock at our parcels ranges from 357.3 ± 32.8 Mg ha^{-1} yr^{-1} (J1895) to 72.5 ± 5.7 Mg C ha^{-1} yr^{-1} at the control parcel that is managed as cropland (Table 29, *Figure 12*). All four chronosequences show a positive correlation between carbon stock and time under AFS management. Both nut orchards planted on cropland as on grassland show an increase on carbon stock.

Table 29 Total C-stock (Sum of carbon in SOC, belowground biomass of trees and grass (BGB) and aboveground biomass (AGB); harvested/pruned wood included).

Parcel		Ar	C2011	C1993		GrNE	C1995		GrNE	J1976	J1966		GrS	J1895
Category	Unit	C-loamy hydro	C-loamy hydro	C-loamy hydro		C-loamy brown	C-loamy brown		J-loamy	J-loamy	J-loamy		J-sandy	J-sandy
SOC-stock (0-60cm)	Mg C ha^{-1}	72.2	71.3	80.8		83.6	134.5		83.6	118.3	161.9		209.1	252.4
BGB-stock	Mg C ha^{-1}	0.3	3.5	6.0		5.9	6.9		5.9	10.4	7.0		3.6	21.4
AGB-grass	Mg C ha^{-1}	0.0	0.6	0.8		1.3	0.8		1.3	0.8	0.8		0.8	0.8
AGB-trees (production)	Mg C ha^{-1}	0.0	3.7	26.9		0.0	27.5		0.0	28.4	14.0		0.0	82.8
Total	Mg C ha^{-1}	72.5 ± 5.7	79.1 ± 4.1	114.5 ± 7.6		90.8 ± 7.9	169.6 ± 10.8		90.8 ± 7.9	157.9 ± 10.2	183.6 ± 14.4		213.4 ± 16.6	357.3 ± 32.8

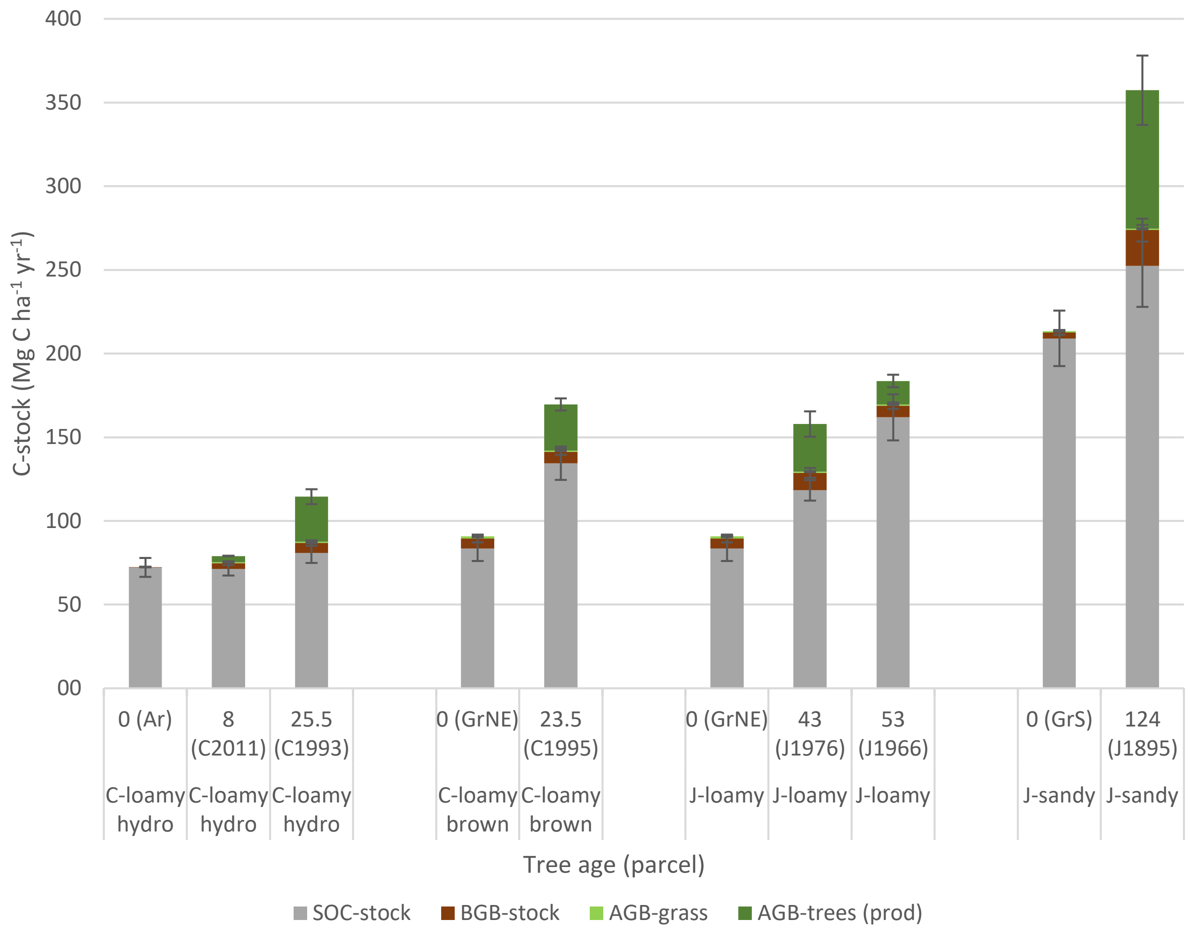

Figure 12 Total C-stock (Sum of SOC 0-60cm, belowground biomass of trees and grass (BGB) and aboveground biomass (AGB), harvested/pruned wood included).

5.6 Total C-fluxes

5.6.1 From C-stock to C-flux

The mean C-flux is 1.72 Mg C ha^{-1} yr^{-1} and ranges from 3.36 at the C1995 parcel to 0.82 Mg C ha^{-1} yr^{-1} (Table 30, Table 31). The total C-flux is not explicitly higher under one specific type of trees. The largest contribution comes from the SOC flux (0.84 Mg C ha^{-1} yr^{-1}), followed by the AGB C-flux (0.71 Mg C ha^{-1} yr^{-1}), BGB C-flux (0.16 Mg C ha^{-1} yr^{-1}) and the AGB C-flux in herbs and grasses (0.01 Mg C ha^{-1} yr^{-1}). The C-flux in biomass (AGB + BGB; trees + herbs & grasses) is almost equal to the SOC flux. The mean Cflux$_{AGB}$: Clux$_{total}$ ratio is app. 4:9 and the Cflux$_{Biomassa}$: SOCflux ratio is about 1:1. Compared to control parcels, C-sequestration in SOC ranges from -/-0.1 to 2.2 Mg C ha^{-1} yr^{-1}, in aboveground biomass from 0.3 to 1.2 Mg C ha^{-1} yr^{-1} and in BGB from 0.02 to 0.4 Mg C ha^{-1} yr^{-1}.

The SOC flux in the Ar control parcel is regarded 0 Mg C ha^{-1} yr^{-1}, so for all parcels that were planted on cropland and have Ar as a control parcel (C2011 and C1993), the baseline C-flux equals the C-flux compared to the control parcel. On average for all tree covered parcels the baseline C-flux is 0.18 Mg C ha^{-1} yr^{-1} (11%) larger than the C-flux compared to the control parcel (0.33 Mg C ha^{-1} yr^{-1} for the GrNE parcel and 0.26 Mg C ha^{-1} yr-1 for the GrS parcel).

Table 30 Total C-flux (compared to control parcel, sum of C-flux in SOC, 0-60cm, belowground biomass of trees and grass (BGB) and above ground biomass (AGB), harvested/pruned wood included).

		C2011	C1993	J1895	J1976	J1966	C1995	Mean
Category	Unit	C-loamy hydro	C-loamy hydro	J-sandy	J-loamy	J-loamy	C-loamy brown	DNA
SOCflux (0-60cm)	Mg ha^{-1} yr^{-1}	-0.119	0.335	0.349	0.805	1.476	2.164	0.835 ± 0.026
$Cflux_{BGB}$	Mg ha^{-1} yr^{-1}	0.408	0.226	0.144	0.106	0.021	0.043	0.158 ± 0.050
$Cflux_{AGB-grass}$	Mg ha^{-1} yr^{-1}	0.076	0.030	0.000	-0.011	-0.009	-0.020	0.011 ± 0.004
$Cflux_{AGB-trees}$	Mg ha^{-1} yr^{-1}	0.457	1.055	0.668	0.661	0.264	1.170	0.712 ± 0.027
$Cflux_{Total}$	Mg ha^{-1} yr^{-1}	0.822 ± 0.163	1.647 ± 0.194	1.161 ± 0.175	1.561 ± 0.178	1.752 ± 0.141	3.356 ± 0.224	1.716 ± 0.011

Table 31 Total C-flux (baseline; compared to status quo. C-flux in BGB & AGB in grass is left aside, because this C-flux is quite variable at a small-time scale and close to zero at a long-time scale. Harvested wood included).

		C2011	C1993	J1895	J1976	J1966	C1995	Mean
Category	Unit	C-loamy hydro	C-loamy hydro	J-sandy	J-loamy	J-loamy	C-loamy brown	DNA
$Cflux_{Total}$ (compared to ref.)	Mg ha^{-1} yr^{-1}	0.822	1.647	1.161	1.561	1.752	3.356	1.716 ± 0.011
$SOCflux_{Control}$	Mg ha^{-1} yr^{-1}	0.000	0.000	0.332	0.258	0.258	0.258	0.184 ± 0.101
$Cflux_{Baseline}$	Mg ha^{-1} yr^{-1}	0.822	1.647	1.493	1.819	2.010	3.614	1.901 ± 0.101

Interpretation of results

The mean C-flux and the range of C-fluxes as determined in our study are in line with the research of Hamon et al (2009) as cited in Aertsens et al. (2013) and Wotherspoon et al. (2014). Our C-fluxes are slightly larger than the values as determined by Cardinael et al. (2017) and smaller than the C-fluxes of Thevathasan and Gordon (2004) (this accounts only for the latter, if the values are extrapolated for SOC). The C-fluxes as found by Palma et al. (2007) and Pardon et al. (2017) are lower than ours, though these studies only took into account either SOC or biomass, determined SOC in a less thick layer, or had a vegetation layer with a strongly aberrant tree density. When these differences would be corrected, then these results would be largely in line with our results too. C-fluxes as found by Dold et al. (2019) and Sharrow and Ismail (2004) are much smaller than our fluxes.

5.6.2 C-flux balance

The mean C-flux balance, input minus output, for all tree covered parcels is 1.027 Mg C ha^{-1} yr^{-1} (Table 32). The C-flux balance can be considered as the balance of photosynthesis and respiration. The net C-flux balance ranges from 2.73 Mg ha^{-1} yr^{-1} at C1995, which has been covered by trees for almost 24 years, to 0.043 Mg ha^{-1} yr^{-1} at C2011, which has been covered by trees for the shortest time.

Table 32 C-fluxes that contribute to the incremental growth.

			C2011	C1993	J1895	J1976	J1966	C1995	Mean
Category	Unit	Remark	C-loamy hydro	C-loamy hydro	J-sandy	J-loamy	J-loamy	C-loamy brown	DNA
$Cflux_{Baseline}$	Mg ha^{-1} yr^{-1}	sum	0.822	1.647	1.493	1.819	2.010	3.614	1.901 ± 0.101
Foliage	*Mg ha^{-1} yr^{-1}*	*to compost*	*0.945*	*1.456*	*7.195*	*2.892*	*1.607*	*1.727*	*2.637 ± 0.573*
Fruits to consumer	*Mg ha^{-1} yr^{-1}*	*out/ to compost*	*0.547*	*0.547*	*0.858*	*0.498*	*0.383*	*0.547*	*0.563 ± 0.064*
Fruits to compost	*Mg ha^{-1} yr^{-1}*	*to compost*	*0.208*	*0.208*	*0.327*	*0.190*	*0.146*	*0.208*	*0.215 ± 0.016*
Prunings	*Mg ha^{-1} yr^{-1}*	*to compost*	*0.085*	*0.085*	*0.000*	*0.000*	*0.000*	*0.085*	*DNA*
$Cflux_{Compost}$	Mg ha^{-1} yr^{-1}	in	0.131	0.131	0.131	0.131	0.131	0.131	0.131 ± 0.026
$Cflux_{Crop}$ (grass)	Mg ha^{-1} yr^{-1}	in	0.380	0.570	0.760	0.760	0.760	0.570	0.633 ± 0.253
$Cflux_{Manure}$ (after 1yr)	Mg ha^{-1} yr^{-1}	in	0.259	0.173	0.000	0.000	0.000	0.173	0.101 ± 0.010
$Cflux_{Lime}$	Mg ha^{-1} yr^{-1}	in	0.009	0.009	0.009	0.009	0.009	0.009	0.009 ± 0.001
$Cflux_{Bal}$	Mg ha^{-1} yr^{-1}	balance	0.043	0.765	0.750	1.042	1.233	2.854	1.027 ± 0.372

Interpretation of results
The $Cflux_{baseline}$ (Eq. 28) is the sum of SOC, BGB and AGB, and ranges from 0.8 Mg C ha^{-1} yr^{-1} (C2011) to 3.6 Mg C ha^{-1} yr^{-1} (C1995). The original input to the compost heap (foliage, fruits, prunings and grasses) is largely exposed to microbial respiration, which explains the difference in input and output of the compost heap. Lime contains a stable kind of carbon, which is not exposed to large microbial respiration and is exposed to limited chemical weathering.

Our C-flux balance ranges from 0.04 to 2.85 Mg C ha^{-1} yr^{-1} which is largely in line with the C-flux balance as determined by Wotherspoon et al. (2014) (0.84 to 2.12 Mg C ha^{-1} yr^{-1}). Our range is larger, in both directions, what might be explained by the fact that the calculations of Wotherspoon were more detailed, including root turnover, root output and C-leachate.

5.7 Soil quality

In general, all four chronosequences show an increased soil and SOM quality as a result of changed land use from cropland or grassland to a nut orchard of *Corylus* or *Juglans*, with improved requirements for the development of stable types of soil organic matter.

The old undisturbed soil of J1895 and GrS (the J-sandy chronosequence) have very high scores on almost all parameters that relate to a good soil quality and a good SOM quality (quality indicators), with slightly better scores for J1895 (Table 33, Table 34, Table 35). Within the C-loamy-hydro chronosequence (Ar, C2011 and C1993) we see that the older the trees, the higher the scores on parameters relating to a good soil quality and a good SOM quality. Within the C-loamy-brown chronosequence (GrNE and C1995) the parcel covered by trees (C1995) scores higher on a good soil quality and a good SOM quality. Within the J-loamy chronosequence we see no clear pattern in the parameters scores in relation to the length of tree coverage, though scores on good soil quality and a good SOM quality seem to be a little better at the parcels covered by trees.

In addition to the quantitative data that was used to describe the quality of the soil, the soil was described in a qualitative way; e.g. describing colour and texture (Appendix C.3).

Table 33 Soil quality of the chronosequence C-loamy hydro (categorized in classes: ≥30% below mean of all parcels (red cells), 11 - 30% below mean (orange cells), +/- 10% of the mean (yellow cells), 11 - 30% above mean (light green) and ≥30% above the mean (dark green)).

			Ar	C2011	C1993
Parameter	Unit	Depth	C-loamy hydro	C-loamy hydro	C-loamy hydro
OM	kg/ha	0-30	-26%	-24%	-20%
C/OM	%	0-30	-5%	-13%	-7%
C/OM	%	30-60	-49%	-34%	-28%
N	kg N/ha	0-30	-22%	-11%	-3%
C/N	dimensionless	0-30	-18%	-25%	-25%
N (delivery cap.)	kg N /ha	0-30	-8%	12%	22%
C/S	dimensionless	0-30	-19%	-19%	-12%
C/P	dimensionless	0-30	-13%	-9%	-56%
pH	grade	0-30	-3%	-5%	10%
Clay-humus	%	0-30	-1%	-22%	17%
CEC	dimensionless	0-30	-2%	-7%	7%
Soil crusting	grade	0-30	-31%	-8%	-7%
SOM annual breakd. (colours reversed, lower is better)	%	0-30	9%	9%	9%
SOM quality	dimensionless	0-30	— —	—	+
Moisture retaining capacity	mm	0-30	-2%	-5%	-3%
pF-appen. point	%	0	1%	-18%	-13%
Micro-biological-activity	mg N/kg	0-30	-42%	-49%	-42%
HWC	mg C/kg DM	0-30	-37%	-4%	6%
Bacteria aerobe	CFU/g	0-30	-6%	66%	16%
Bacteria anaerobe	CFU/g	0-30	-62%	44%	68%
Fungi, yeasts	CFU/g	0-30	-12%	-16%	-16%
Earthworms	kg/ha	0-30	-82%	no data	44%
Earthworms	Kg/ha	30-60	-100%	no data	-6%

Corylus trees planted on cropland seem to have a positive effect on soil quality, since the amount of parameters with a higher score (green cells) seems to increase over time.

Table 34 Soil quality of the chronosequence J-sandy (categorized in classes: ≥30% below mean of all parcels (red cells), 11 - 30% below mean (orange cells), +/- 10% of the mean (yellow cells), 11 - 30% above mean (light green) and ≥30% above the mean (dark green). No data collected on HWC, bacteria or fungi/yeasts).

			GrS	J1895
Parameter	**Unit**	**Depth**	**J-sandy**	**J-sandy**
OM	kg/ha	0-30	37%	42%
C/OM	%	0-30	14%	5%
C/OM	%	30-60	56%	32%
N	kg N/ha	0-30	24%	27%
C/N	dimensionless	0-30	13%	28%
N (delivery cap.)	kg N /ha	0-30	12%	-3%
C/S	dimensionless	0-30	52%	3%
C/P	dimensionless	0-30	72%	65%
pH	grade	0-30	-11%	-1%
Clay-humus	%	0-30	-5%	59%
CEC	dimensionless	0-30	-13%	5%
Soil crusting	grade	0-30	9%	15%
SOM annual breakd.	%	0-30	-9%	-15%
SOM quality	grade	0-30	+	++
Moisture retaining capacity	mm	0-30	10%	-5%
pF-appen. point	%	0	16%	28%
Micro-biolological-activity	mg N/kg	0-30	26%	110%
Earthworms	kg/ha	0-30	-32%	-48%
Earthworms	Kg/ha	30-60	-6%	134%

Juglans trees planted on grassland seem to have a slightly positive effect on soil quality, since the scores seem to increase (with time). The amount of parameters with a low score (orange cells) shrinks and the amount of parameters with a high score (green cells) grows over time.

Table 35 Soil quality of the chronosequences C-loamy brown and J-loamy (categorized in classes: ≥30% below mean of all parcels (red cells), 11 - 30% below mean (orange cells), +/- 10% of the mean (yellow cells), 11 - 30% above mean (light green) and ≥30% above the mean (dark green)).

			GrNE	C1995	J1976	J1966
Parameter	**Unit**	**Depth**	**C-loamy Brown /J-loamy**	**C-loamy brown**	**J-loamy**	**J-loamy**
OM	kg/ha	0-30	-12%	-8%	5%	7%
C/OM	%	0-30	2%	4%	0%	1%
C/OM	%	30-60	-12%	21%	-16%	29%
N	kg N/ha	0-30	4%	-24%	8%	-3%
C/N	dimensionless	0-30	-18%	28%	-3%	20%
N (delivery cap.)	kg N /ha	0-30	17%	-39%	7%	-19%
C/P	dimensionless	0-30	-54%	-31%	40%	-13%
C/S	dimensionless	0-30	-21%	17%	-13%	13%
pH	grade	0-30	19%	2%	-1%	-9%
Clay-humus	%	0-30	-32%	12%	10%	-37%
CEC	%	0-30	9%	7%	-3%	-3%
Soil crusting	grade	0-30	3%	7%	7%	5%
SOM annual breakd.	%	0-30	9%	-9%	3%	-3%
SOM quality	grade	0-30	—	+/—	++	+
Moisture retaining capacity	mm	0-30	2%	-10%	5%	7%
pF-appen. point	%	0	-14%	-1%	3%	-4%
Micro-biolological-activity	mg N/kg	0-30	19%	-28%	28%	-23%
HWC	Mg C/kg DM	0-30	-34%	25%	no data	no data
Bacteria aerobe	CFU/g	0-30	-47%	-37%	no data	no data
Bacteria anaerobe	CFU/g	0-30	-66%	-28%	no data	no data
Fungi, yeasts	CFU/g	0-30	-52%	63%	no data	no data
Earthworms	kg/ha	0-30	no data	118%	no data	no data
Earthworms	Kg/ha	30-60	no data	-22%	no data	no data

Juglans and *Corylus* trees planted on grassland seem to have a small positive effect on soil quality, since the scores seem to increase little (over time). The amount parameters with a low score (red or orange cells) is reduced over time.

We compared our data (Table 36) to our target values as elaborated in Ch. 4 (Table 6), to categorize our findings; supported by colours (Table 36).

Table 36 Parameter values indicating the quality of the soil and the SOM (all parameters are indicators of soil quality, only the upper 9 parameters are indicative for SOM quality. Categorized in classes: within target range (light green), below target range (orange), above target range (dark green), values are compared to target values of Table 6, for SOM annual breakdown range is 2.0 +/- 10%, for earthworms, 0-30cm, range is 700kg +/- 50%, and for earthworms, 30-60cm, range is 80kg +/- 50%, n.d. = no data).

				Ar	C2011	C1993	GrS	J1895	GrNE	J1976	J1966	C1995
Parameter	Unit	Target	Quality	C-loamy hydro	C-loamy hydro	C-loamy hydro	J-sandy	J-sandy	C-loamy brown/J-loamy	J-loamy	J-loamy	C-loamy brown
C/OM	%	0.45-0.55	Soil + SOM	0.46	0.42	0.45	0.55	0.51	0.49	0.48	0.49	0.50
SOM annual breakdown	%	1.8-2.2	Soil + SOM	1.8	1.8	1.8	1.5	1.4	1.8	1.7	1.6	1.5
C/N	dimension - less	13-17	Soil + SOM	11	10	10	15	17	11	13	16	17
C/S	dimension - less	50-75	Soil + SOM	61	61	66	114	77	59	65	85	88
Clay-humus	%	44-93	Soil + SOM	58.5	46	69	56	94	40	65	37	66
CEC	dimension - less	>95	Soil + SOM	89.5	85	98	80	96	100	89	89	98
C/P	dimension - less	≥100	Soil + SOM	90	95	45	179	172	48	145	91	72
HWC	mg C/ kg DM	700-2300	Soil + SOM	469	707	782	875	n.d.	489	n.d.	n.d.	923
Earthworms	kg/ha [0-30]cm	350-1050	Soil + SOM	160	n.d.	1300	613.3	466.7	n.d.	n.d.	n.d.	1960
Earthworms	kg/ha [30-60cm]	40-120	Soil + SOM	0	n.d.	80	80	200	n.d.	n.d.	n.d.	66.7
N-stock	kg N/ha	3950-5610	Soil	5210	5900	6470	8220	8450	6900	7190	6430	5060
N (delivery cap.)	kg N /ha	95-145	Soil	90	110	120	110	95	115	105	80	60
pH	grade	5.5-6.3	Soil	5.1	5.0	5.8	4.7	5.2	6.3	5.2	4.8	5.4
Soil crusting	grade	6.0-8.0	Soil	5.2	6.9	7	8.2	8.6	7.7	8	7.9	8

5.8 Model

Our model (CANOE; §4.6 and Appendix B.3; Figure 15) is based on C-stock data for different categories collected at our study area at Breedenbroek and processed into fluxes with Eq. 1. The model uses soil type, SOC-concentrations, tree age, species and grass cover as input and has C-stocks as output (Table 37). For the C-loamy brown and J-sandy chronosequences the results of CANOE are almost identical to the field data. For the other two chronosequences the output of CANOE is either smaller than the field data (-/-22%; C-loamy hydro) or larger (+15%; J-loamy). The model was not tested on any nut orchard outside our study area.

Table 37 Model C-stock growth compared to control parcels. Findings based on one run for each chronosequence, with a time length of the oldest parcel and a mean flux based on all tree parcels in chronosequence.

Parcel			C1993		C1995		J1966		J1895
Category	Unit	Source	C-loamy hydro		C-loamy brown		J-loamy		J-sandy
SOC-stock (0-60cm)	Mg C ha^{-1}	Field data	8.6		50.8		78.2		43.3
BGB-stock	Mg C ha^{-1}	Field data	6.0		6.9		1.1		17.8
AGB-grass	Mg C ha^{-1}	Field data	0.8		0.8		-0.5		0.0
AGB-trees (production)	Mg C ha^{-1}	Field data	26.9		27.5		14.0		82.8
Total	**Mg C ha^{-1}**	**Field data**	**42.2**		**78.9**		**92.9**		**143.9**
SOC-stock (0-60cm)	Mg C ha^{-1}	CANOE	7.5		48.8		76.8		43.0
BGB-stock grass	Mg C ha^{-1}	CANOE	3.3		0.0		0.0		0.0
BGB-stock trees	Mg C ha^{-1}	CANOE	2.3		3.2		5.8		17.7
AGB-grass	Mg C ha^{-1}	CANOE	0.7		0.0		0.0		0.0
AGB-trees (production)	Mg C ha^{-1}	CANOE	18.9		26.9		24.0		82.2
Total (deviation)	**Mg C ha^{-1}**	**CANOE**	**32,7 (-22%)**		**78.9 (0%)**		**106.6 (15%)**		**143.0 (1%)**

Interpretation of results

Small differences between the output of the field data and the model for the C-loamy brown and J-sandy chronosequences are a result of some necessary generalisations that had to be made. Otherwise, CANOE would have become too complicated. The large differences between output from the field data and the model can be explained by the fact that growth values in the model were based on the mean of two tree covered parcels that are part of the C-loamy hydro chronosequence and the mean of the two tree covered parcels that are part of the J-loamy chronosequence.

The model also shows how much carbon is removed as pruned and thinned wood. The size of the C-stock grows gradually each year, though in reality the thinning (removing complete rows) will not be executed gradually, but by a few systematic thinnings that will take place in a few years, with many years between them. This simplification was also applied to keep the model simple. It would be interesting to add the planting density to the model.

5.9 Sensitivity analysis

We tested the sensitivity of the amount C per hectare to three investigated parameters:

1. SOC stock to changes in soil bulk density
2. C-stock to changes in soil A-horizon depths
3. C-stock to changed chronosequence control parcels

SOC stock and changes in soil bulk density

Soil mass was estimated by a laboratory, based upon interrelations between physical and chemical quantities of soil samples gathered outside the study area. We converted this soil masses into a bulk density. The bulk densities of J1895 and C1995 were exceptionally low, since according to Structx (n.d.) the soil bulk density of (silty) sand is 1430 kg m^{-3}. Therefore, we based all calculations at the mean of all our bulk density sampling results; 1267.2 ± 43.8 (Table 38).

By applicating Eq. 34 the sensitivity turned out to be 1.0. Calculations based on the mean soil bulk density result in significantly (up to 31%) higher C-stocks at parcels for which the estimated soil bulk density had a large deviation from the mean soil bulk density (e.g. J1895).

Table 38 SOC stock sensitivity analysis.

Category	Type	Code	Depth (cm)	Ar1	Ar2	C2011	C1993	GrS	J1895	GrNE	J1976	J1966	C1995
Bulk density (laboratory)	Parameter	P_o		1365.4	1370.2	1365.4	1356.1	1233.6	967.7	1337.7	1302.6	1298.3	1074.9
Bulk density (mean)	Parameter	P_i		1267.2	1267.2	1267.2	1267.2	1267.2	1267.2	1267.2	1267.2	1267.2	1267.2
Mg C ha^{-1}	Model out	Out_o	0-30	57.3	57.5	60.4	62.0	129.5	111.4	72.2	94.2	99.6	78.6
Mg C ha^{-1}	Model out	Out_i	0-30	53.2	53.2	56.1	58.0	133.1	145.9	68.4	91.7	97.3	92.7
Mg C ha^{-1}	Model out	Out_o	30-60	20.5	20.6	16.4	24.4	74.0	81.3	16.1	27.4	66.2	35.5
Mg C ha^{-1}	Model out	Out_i	30-60	19.0	19.0	15.2	22.8	76.0	106.4	15.2	26.6	64.6	41.8
Sensitivity			0-60	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Deviation (%)			0-60	-7.20	-7.52	-7.20	-6.55	2.72	30.95	-5.27	-2.72	-2.40	17.89

SOC-stock and changes in soil A-horizon depths

C-stock amounts calculated based on the boundary between the A- and B-horizon instead of a strict boundary at a depth of 30 cm turn out to result in 3.8% to 15.8% higher C-stocks in the 0-60 cm zone (Table 39).

Table 39 A-horizon depth sensitivity analysis.

Category	Unit	Value	Ar	C2011	C1993	GrS	J1895	GrNE	J1976	J1966	C1995
Soil description (App. 9)	code		G5	G9	G1, G2, G3, G8	G13	G14	G6, G7	G12	G11	G10
Boundary of A-Horizon	cm		33	32	30	30	Indistinct	35	35	Indistinct	42.5
Soil Organic Carbon	kg/ha	0-30	53222	56073	57974	133054	145927	68428	91656	97254	92663
Soil Organic Carbon	kg/ha	30-60	19008	15206	22809	76031	106443	15206	26611	64626	41817
Soil Organic Carbon	kg/ha	0-60	72229	71279	80783	209085	252370	83634	118267	161881	134480
Soil Organic Carbon	kg/ha	A-Hor	58544	59811	57974	133054	145927	79833	106932	97254	131272
Soil Organic Carbon	kg/ha	B-Hor (<60)	17107	14192	22809	76031	106443	12672	22176	64626	24393
Soil Organic Carbon	kg/ha	A+B-Hor (<60)	75651	74003	80783	209085	252370	92504	129107	161881	155665
Sensitivity	rate		0.47	0.57	DNA	DNA	DNA	0.64	0.55	DNA	0.38
Deviation (%)	%	A+B-Hor (<60)	4.74	3.82	DNA	DNA	DNA	10.61	9.17	DNA	15.75

Some parcels had no distinct boundary between the A- and B-horizon, therefore the C-stocks for these parcels were not recalculated. These higher C-stocks do not necessary lead to higher sequestration rates, since the C-stocks of our control parcels also increased.

By applicating Eq. 34 the sensitivity turned out to be 0.38 to 0.64. We decided to hold on to our original classification, based on a default boundary of 30 cm, instead of classes based on a stratification, for the next reasons:

1. Most of the literature we studied, e.g. FAO (2019a); Y. Zhang and Hartemink (2017), is based on unremitted decimetres, like the 0-30 cm class, and advises to uniform sampling depths. A uniform sampling depth makes it easier to compare sampling depths. According to Nair (2012) a uniform breaking point between soil-horizon depths is still lacking.
2. The majority of the depths of the boundaries we collected (Table 39) is based on a single soil pit or hand augered soil sample. Spatial variety is likely to be several cm or even dm, what makes the results unreliable.
3. It is not easy to determine a precise level of the boundary, because a hand auger is not a precision instrument and easily mixes up the soil.
4. Collecting soil samples was done based on a strict classification of 0-30 and 30-60 cm depth. If an A-horizon stretched into the 30-60 cm class the A-horizon that was part of the 30-60 cm zone was proportionally mixed into the 30-60-cm-sample.

Potential errors, in relation to sampling depth fluctuations while taking samples, were not elaborated in the standard error of our results.

SOC-flux and former land use management of control parcels

When SOC flux calculations are based on control parcels with a different historic land use management (Ar and GrS instead of the selected control parcel GrNE; all within a range of 500 m), than the output for 0-60 cm depth might have been 246.7% smaller or up to 22.4% higher (Table 40).

Table 40 Former land use management sensitivity analysis (Sensitivity could not be calculated with the use of Eq. 34, because the input was not numeric, but spatial).

Category	Unit	Code	Depth (cm)	C1995 with control Ar	Deviation i.r.t. GrNE	C1995 with control GrS	Deviation i.r.t. GrNE	C1995 with control GrNE
SOCflux	Mg C ha^{-1} yr^{-1}	Out	0-30	1.68	62.7%	-1.72	-266.7%	1.03
SOCflux	Mg C ha^{-1} yr^{-1}	Out	30-60	0.97	-14.3%	-1.46	-228.6%	1.13
SOCflux	Mg C ha^{-1} yr^{-1}	Out	0-60	2.65	22.4%	-3.17	-246.7%	2.16

The composition of chronosequences is sensitive to differences in former land use management. Control parcels within a range of 500 m do already have large differences in C-concentrations (input for our C-flux calculations). If the distance between different parcels of the same chronosequence is larger, differences in historic land use management are likely to be even larger and results to be more insecure. This might lead to larger deviations and emphasizes the concern that has to be taken into account when compiling chronosequences and interpreting results.

6 Discussion and conclusions

In this master's thesis we studied the question at which rate carbon sequestration changes by converting agricultural land into nut orchards, as a kind of AFS, in the temperate climate of the Netherlands. In our search for answers, we focused on designing the system in terms of carbon stocks and carbon fluxes. We tried to synthesise the carbon sequestration dynamics in this AFS in a model, which was compared with calculated results from the field survey.

The next paragraph discusses how we can answer this question. In the subsequent paragraph (conclusion) we provide an answer to the key research question, at hand of the three sub-questions and our perspective of whether our results and modelled future pathways can make a contribution to enhancing carbon sequestration by turning agricultural land into agroforestry systems like nut orchards.

6.1 Discussion

In the section on Methodology we reflect on the validity and importance of the research setup of field survey along chronosequences and modelling of carbon sequestration. In section carbon sequestration we discuss the findings on carbon stocks, carbon fluxes and soil quality. In section Impact we elaborate the aim of the study to mitigate CO_2 emissions and which kind of mechanisms play a role comparing nut orchards, as a kind of AFS, with conventional agricultural land use.

Methodology

To answer our research question a C-budget based methodology was designed, grounded on the use of chronosequences and the gathering of field data. In addition, a C-budget based model was designed. Time studies are a very accurate way to monitor C-sequestration changes. In those situations that time studies are not applicable, chronosequences can be a good alternative to time studies. A chronosequence is defined as a series of locations which had a comparable land use management under comparable environmental conditions, but with different ages. The composition of chronosequences, as shown in our sensitivity analysis, is of large influence on the calculated C-sequestration. Our findings show the importance of compiling chronosequences with parcels that have uniform parameter values. The parcels J1966 and J1976 contain different varieties of *Juglans*, which have different growing speeds. The Juglans of J1966 is a slow growing tree compared to J1976, which is expected to have a more common growing speed. Excluding parcel J1966 from the J-loamy chronosequence results in a 44% higher AGB C-flux than the mean of J1966 and J1976, and a 29% lower mean SOC-flux. This higher AGB C-flux can be explained by the difference in tree growing speeds; an explanation for the lower SOC-flux might be that J1966 and J1976 have a slightly different land use management history. Chronosequences might be a good alternative to time studies, however only under the condition of careful selection of the locations and parameters and controlled by the elaboration of a sensitivity analysis. A global soil carbon monitoring, reporting and verification platform (Smith et al., 2020), preferably with a special section on chronosequences, might help to improve the reliability of chronosequence studies.

A limitation to the reliability of our research method is that some parameters were based on literature, or were estimated with the help of allometric equations: dry matter content, BGB volumes, leaf-content of biomass and AGB volume of *Juglans*. Bulk density was not determined directly either, but estimated on the basis of sampling results of multiple external locations by the laboratory. Collecting local data on all these parameters would have contributed to the accuracy of our results; e.g. bulk density turned out to have a sensitivity of 1 in relation to the C-stock. For future research on carbon sequestration the elaboration of AFS-specific allometric equations would be of great help to attain increased reliability.

Soil organic carbon

The reliability of our results for the 0-30 cm soil layer is higher than those for 30-60 cm. To obtain reliable results for soil sampling by analysing only a limited amount of samples in a laboratory, the FAO (2019a) recommends the method of composite samples at strata in combination with pre-sampling. In the 0-30 cm zone we did apply the method of composite sampling at strata (based at about 40 cores), though without pre-sampling. We also took only one or two, instead of the recommended number of at least three composite samples per stratum (FAO, 2019a), so the reliability of our soil samples is not as high as preferred. In the 30-60 cm soil layer our samples were based on just two cores, instead of 40 cores in the 0-30 cm zone, which strongly reduces the reliability of our 30-60 cm zone results.

The modelled pathways for SOC sequestration have no maximum level of SOC stock. In the long run soil capacity to store carbon, especially in the sandy soils of the Netherlands with less than 10% of clay, might be limited to a SOC level of 7% (Merante et al., 2017). SOC levels in our orchards of study are still well below this level (1.5%-3.8%; 0-30 cm depth). Within our study area parcel J1895 has the highest SOC level (3.8%) and the lowest clay fraction (3%). Therefore, it is likely that other parcels in our study area, which have equal or higher clay fractions, must be able to reach SOC level of at least 3.8% and maybe up to 7%.

Aboveground biomass

For biomass our pathways have no maximum C-stock too. We should realize that trees will not live forever, but it is possible to replace trees at some point in time, after which new wood will grow. In our study AGB C-stocks and AGB C-fluxes were based on both the amount of biomass that is still present in the study area, as on the amount of biomass that has been removed as pruned wood and cut trees. These prunings and cut trees were used as fuel, so they prevented fossil emissions, or could have been turned into biochar and stored in the soil, which made it reasonable to us to add this biomass carbon to the total amount of stored carbon.

Carbon sequestration

Soil organic carbon

All the orchards, except the one which has only recently been turned into an orchard, have a larger SOC stock than their control parcels (either cropland or grassland). The SOC-stock (and so the SOC-flux) in the 30-60 cm zone might be slightly overestimated. Soil samples at a 30-60 cm depth at the *Corylus* parcels were only collected in the tree row (S1) stratum, because for the 0-30cm zone C-concentrations where larger in the S1 stratum than in the S2 stratum. At the *Juglans* parcel the 30-60 cm depth samples were taken at a distance of 3 m, which is expected to be more representative. C-sampling was located outside the locations where *Corylus* trees used to stay in the field and which had been cut leaving the roots in the soil, after having been chopped. This means that it is likely that these unsampled locations will contain relatively high levels of carbon.

We only calculated the SOC stock and SOC flux until a depth of 60 cm. Beneath that depth an increase of SOC-stock is likely too, because we encountered some tree roots and larger amounts of earthworms in this zone in the tree covered parcels compared to the control parcels. Earthworms transport OM through the soil, help to increase soil quality and carbon stability (Van Eekeren et al., 2014). The larger amounts of earthworms we detected might in the long run contribute to higher levels of stable carbon and an increased capacity of the soil to store carbon.

Biomass

All tree covered parcels have a much larger current biomass C-stock than their control parcels; both for *Corylus* and for *Juglans* (mean current biomass C-stock is about 13k% larger than current biomass C-stock at cropland and 547% larger than grassland). The findings on AGB of *Corylus* parcels are statistically not very reliable, since current wood volume calculations were based on the wood volume of just one model tree (so called destructive measuring of a model tree) and harvested wood volume calculations were based on incomplete data. For *Juglans* the reliability of our findings on AGB and BGB (and on SOC) is limited too, because all of our *Juglans* parcels only contain one tree.

Additional research on C-sequestration rates of tree varieties might reveal an increased potential of C-sequestration in woody biomass of specific tree varieties, since some varieties, e.g. *Juglans Broadview*, are known to be fast growing. At the *Corylus* parcels all soil sampling took place under the variety named Gunslebert and at the *Juglans* parcels we were unable to compose complete chronosequences of one tree variety. This means that reliability of results can be improved by additional research at different tree varieties. Additional research on planting distances and the multitude of AFS practices, as described by Kay et al. (2019), might reveal valuable new insights on carbon sequestration too.

The amount of undetected carbon in BGB might be almost as large as the current BGB at the C1993 and C1995 parcels. So especially the insecurity of allometric equation-based C-stocks in BGB is large. For more large scale research the use of big data, like measuring AGB with the help of remote sensing as described by Jucker et al. (2017), might be of help.

Total carbon sequestration

The mean C-flux generated by LUC to nut orchards, as a form of AFS, is 1.72 Mg C ha^{-1} yr^{-1} (0-60 cm depth). This is 5.3 times higher than the sequestration rate Batjes (2019) found for cropland in a medium climate under wet conditions (0.2-0.45 Mg C ha^{-1} yr^{-1}, 0-30 cm depth). Our mean C-flux is 4.0 times larger than the C-flux we determined for grassland largely based on Van Eekeren and Zaneveld-Reijnders (2011) (0.38-0.49 Mg C ha^{-1} yr^{-1}, 0-30 cm depth). Looking at other land use types it is interesting to look at Arets et al. (2019) who estimated the C-flux in biomass in fruit orchards in the Netherlands at 2.1 Mg C ha^{-1} yr^{-1}. It is feasible that SOC-accumulation in fruit orchards is positive too, because nut orchards have a lot of parameters in common with fruit orchards. Additional research on fruit orchards therefore would be interesting. In our study, as was the case in many other AFS C-sequestration studies, we presumed C-sequestration to be a linear process, though we recognized some non-linear events, like thinning and a lower C-flux in the oldest *Juglans*-parcel. These findings are in line with the non-linear -sequestration results of Dold et al. (2019), so future long-term research on the non-linear characteristics of C-sequestration is recommended.

A study by Teixeira et al. (2008) in the Mediterranean revealed that biodiverse sown grasslands might sequester as much as 1.23 – 1.44 Mg C ha^{-1} yr^{-1}. The growth at the our grassland control parcels is estimated at 0.38 Mg C ha^{-1} yr^{-1} for the GrNE parcel and 0.49 Mg C ha^{-1} $yr^{-}1$ for the GrS parcel., so managing the grass alleys between the tree rows as suggested by Teixeira et al. (2008) might also add to additional C-sequestration.

Impact

Soil organic carbon

The goal of the research programme, called 'quatre-promille' (related to the Paris agreement), is to mitigate CO_2 emissions by increasing SOC with 0,4% per year (Minasny et al., 2017). Translating our SOC sequestration rates (0-60cm) into a permillage results in a SOC flux range of -/-2‰ yr^{-1} to +60‰ yr^{-1} (mean +22‰ yr^{-1}). So, the 'quatre-promille' targets seem to be a well reachable goal, by land use change to nut orchards and comparable AFS, in the temperate zone of the Netherlands.

Total sequestration in agroforestry systems

Carbon sequestration by agroforestry can contribute to the goals of the Paris agreement to lower Carbon dioxide (CO_2) in the atmosphere. The Dutch climate agreement obliges the agriculture and land use sector to reduce its emissions by 3.5 Mton CO_2 eq. yr^{-1}, to which agroforestry might contribute a reduction of 1.1 Mton CO_2 eq. yr^{-1} ($0.30 \cdot 10^6$ Mg C yr^{-1}) (Keur & Selin Noren, 2019). This would require the transition of about 175k ha conventional agricultural management into AFS systems and would offset 0.67% of the Dutch annual carbon emissions (163 Mton CO_2 yr^{-1}, 2017 (CBS RIVM/Emissieregistratie, 2018)). This area is 34% larger than the area that corresponds with the potential nut sells in the Netherlands (130,000 ha (Baltissen & Oosterbaan, 2017)), though other agroforestry systems, e.g. combinations with fruit orchards, are possible

The potential to mitigate CO_2-emissions might even be larger, because agroforestry can also reduce N_2O emissions, which is one of the GHGs (Keur & Selin Noren, 2019). For the Netherlands CO_2-sequestration by stimulating nut-production based AFS can be well combined with establishing low nitrogen emission and biodiversity enhancing buffer zones around Natura 2000 areas.

The European Green Deal sets goals for clean energy production, food production, sustainable use of resources and to some degree also restoring natural ecosystems (European Commission, 2019) and suggests to take up the challenge by planting trees (afforestation) as one of the means to reach these goals (Vaughan, 2020). LUC to agroforestry is likely to contribute to many of these goals if a substantial share of conventional agricultural land would be transformed into AFS, and could be an alternative or supplement to the EU suggested afforestation. Our C-sequestration values fall within the range of potential C-sequestration values as described by Kay et al. (2019) for the many varieties of AFS that could be applied in the EU. The maximum potential of new AFS in the EU could be as much as 2,1 to $64 \cdot 10^6$ Mg C yr^{-1}, which corresponds to 4.8% to 144.1% of the Dutch C-emissions. This would require 8.9% of the EU agricultural area to be turned into AFS.

At a global level it is hard to upscale the implications of our findings, with such a large variety in soil, climate and different AFS. C-stocks generally increase when land use changes from crop- or grassland to AFS, though for instance the conversion of forest into agroforestry will lead to losses in SOC in the top layers (De Stefano & Jacobson, 2018). Further research on the local and global potential of C-sequestration is worth the effort, because the IPCC (Watson et al., 2000) estimated that 630 Mha of unproductive grass- and croplands can be converted into agroforestry, so the global potential might be enormous.

6.2 Conclusions

At which rate do Carbon stocks, Carbon fluxes and Soil Quality change after converting agricultural grassland respectively cropland into Corylus and Juglans orchards on sandy and loamy sand soils in the temperate zone of Gelderland?

Which characteristics of carbon sequestration in nut orchards, cropland and grasslands are representative and easily measurable?

We concluded that the main characteristics of soil carbon sequestration in nut plantations, cropland and grassland are the SOC, SOM and bulk density. SOC and SOM can easily be measured by analysing soil samples in a laboratory and should be gathered at a depth of 0-30 cm and if possible, also at a depth of 30-60 cm. Measuring soil bulk density is more complex, but this number can also be based on literature.

The main characteristics of carbon sequestration in biomass are the amount of carbon stored in wood, herbs and grasses, roots and harvested wood. Except for the data on carbon in roots, all data can easily be gathered by fieldwork. Data on carbon in roots can be generated with the help of allometric equations.

Which physical, chemical and biological characteristics of the soil quality are representative and easily measurable?

Important characteristics of SOM and soil quality that are easily measurable by laboratory analysis are the SOC and SOM, CEC, HWC and the amount of earthworms and the C/OM, C/N, C/S, C/P and Clay-humus ratios.

How large are C-stocks and C-fluxes in various nut orchards, soils and comparable previous agricultural management systems at sandy and loamy sand soils in Gelderland?

This study showed that all our four chronosequences of nut orchards containing *Corylus avellana* and *Juglans regia* at sandy and loamy sand soils in the temperate climate of Gelderland, the Netherlands, show a positive correlation between carbon stock and time under AFS management. Both nut orchards planted on cropland as on grassland show an increase of C-stock, so AFS sequesters more carbon than conventional agricultural management under the local conditions.

Total C-sequestration rate, compared to conventional agricultural management, ranges from 0.8 to 3.4 Mg C ha^{-1} yr^{-1} (mean 1.72 Mg C ha^{-1} yr^{-1}). The total C-flux is not explicitly higher under one specific type of trees. The largest contribution comes from the SOC flux (0.84 Mg C ha-1 yr-1), followed by the AGB-C-flux (0.71 Mg C ha-1 yr-1), BGB-C-flux (0.16 Mg C ha-1 yr-1) and the AGB-C-flux in herbs and grasses (0.01 Mg C ha-1 yr-1). Overall, our results confirm the C-sequestration potential of changing grass- and cropland into nut orchards in the temperate zone to mitigate global CO_2 emissions and are in line with previously elaborated comparable studies.

How does a model to predict future pathways for C-sequestration in soil and vegetation look like for Corylus and Juglans orchards at sandy and loamy sand soils in Gelderland?

A mathematical model can predict future pathways of C-sequestration in nut orchards accurately by displaying the growth of C-stocks. When the model is based on the mean C-sequestration of multiple parcels, then the deviation of output is large (-/-22% to +15%).

What is the quality of the soil organic matter under nut orchards and comparable cropland respectively grassland at sandy and loamy sand soils in Gelderland?

In general, all four chronosequences show an increased soil and SOM quality as a result of changed land use from cropland or grassland to a nut orchard of *Corylus* or *Juglans*, with improved requirements for the development of stable types of soil organic matter.

Our study confirms the discourse that agroforestry can play a large role in offsetting national, European and global carbon emissions and contribute to an increased soil quality and food production at the same time.

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Appendices

Appendix A Study area

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Appendix A.1 Study area: Parcel locations

Appendix A.2 Study area: Soil types

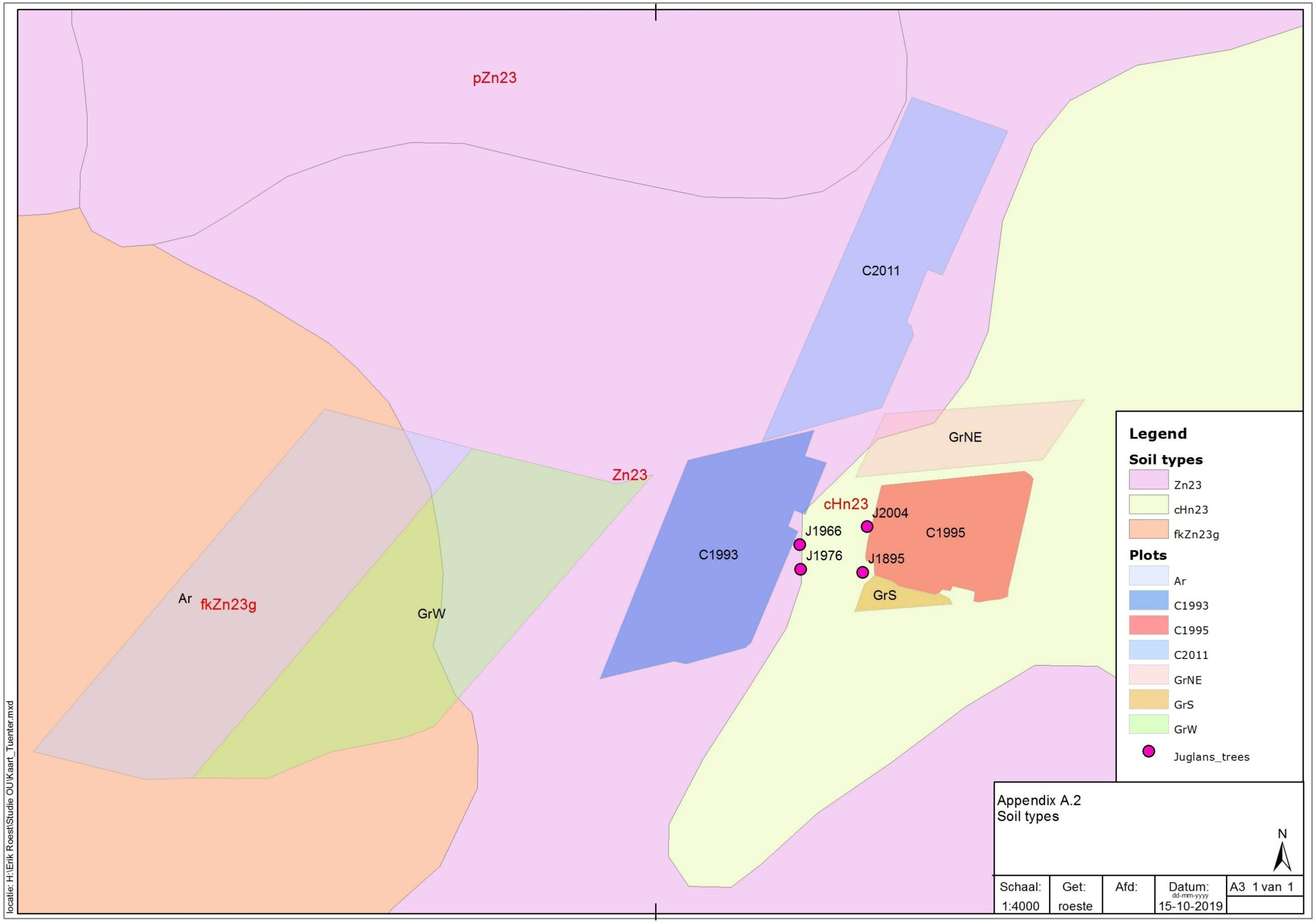
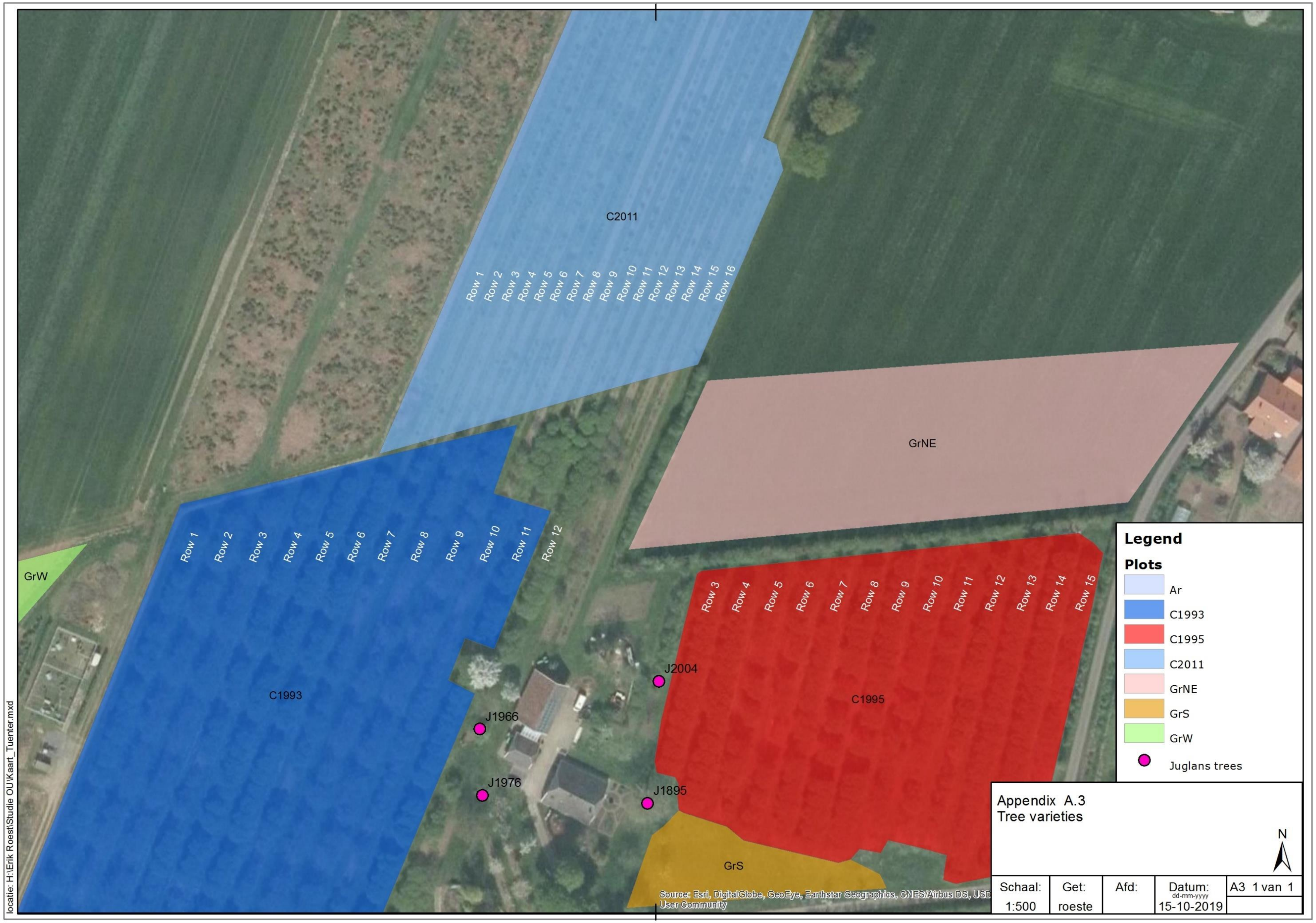


Table 41 Physical quantities of the soil (sampling locations: Appendix A.4).

Parcel		**Depth (cm)**	**Ar**	**C2011**	**C1993**	**GrS**	**J1895**	**GrNE**	**J1976**	**J1966**	**C1995**
Chronosequence			**C-loamy hydro**	**C-loamy hydro**	**C-loamy hydro**	**J-sandy**	**J-sandy**	**C-loamy brown/J-loamy**	**J-loamy**	**J-loamy**	**C-loamy brown**
Parameter											
Soil class (NL)			fkZn23g	Zn23	Zn23	cHn23	cHN23	cHn23	Zn23/cHn23	Zn23/cHn23	cHn23
Clay	%	0-30	8	6	6	4	3	3	5	3	3
Silt	%	0-30	17	12	13	12	9	16	15	15	15
Sand	%	0-30	72	79	78	78	80	77	76	77	77
Clay-humus	%	0-30	58.5	46	69	56	94	40	65	37	66
Soil structure		0-30	-	--	+/++	--	+	-	+/-	-	+
Texture		0-30	loam/loamy sand	sand/loamy sand	sand/loamy sand	sand	sand	sand/loamy sand	sand/loamy sand	sand/loamy sand	sand/loamy sand

Appendix A.3 Study area: Tree varieties



Appendix A.4 Study area: Sampling locations

Appendix A.5 Study area: Details

Details gathered by gathering field management information from the owners of the parcels in the winter of 2018/2019 (Table 42).

Table 42 Tree rows and tree varieties.

Parcel	Row (for location, see Appendix A.3)	Corylus Avellana variety
C1993	1	7 Cosfort+Impériatrice Eugénie
C1993	2	5 Lang Tidlig Zeller
C1993	3	5 Lang Tidlig Zeller
C1993	4	7 Cosfort+Impériatrice Eugénie
C1993	5	3 Gunslebert
C1993	6	3 Gunslebert
C1993	7	7 Cosfort+Impériatrice Eugénie
C1993	8	5 Lang Tidlig Zeller
C1993	9	5 Lang Tidlig Zeller
C1993	10	6 Lange Spaanse
C1993	11	3 Gunslebert
C1993	12	3 Gunslebert
C1995	1	7 Cosfort.Impériatrice Eugénie
C1995	2	2 EMOA 1
C1995	3	3 Gunslebert
C1995	4	3 Gunslebert
C1995	5	4 Gustav's Zeller
C1995	6	4 Gustav's Zeller
C1995	7	7 Cosfort.Impériatrice Eugénie
C1995	8	3 Gunslebert
C1995	9	3 Gunslebert
C1995	10	4 Gustav's Zeller
C1995	11	4 Gustav's Zeller
C1995	12	9 Tonda di Giffoni+Webb's Price Cob
C1995	13	3 Gunslebert
C1995	14	3 Gunslebert
C1995	15	7 Cosfort.Impériatrice Eugénie
C2011	1	1 Corabel
C2011	2	8 Cosfort+EMOA 1
C2011	3	1 Corabel
C2011	4	5 Lang Tidlig Zeller
C2011	5	4 Gustav's Zeller
C2011	6	4 Gustav's Zeller
C2011	7	8 Cosfort+EMOA 1
C2011	8	6 Lange Spaanse
C2011	9	3 Gunslebert
C2011	10	3 Gunslebert
C2011	11	8 Cosfort+EMOA 1
C2011	12	4 Gustav's Zeller
C2011	13	4 Gustav's Zeller
C2011	14	2 EMOA 1
C2011	15	2 EMOA 1
C2011	16	2 EMOA 1

History

Around 1930 large parts of the area have been levelled by adding soil underneath or mixing with the topsoil. This probably took place at the parcels GrW and C2011 and maybe other parts of area, but not at the Juglans parcels. In 1980/1981 the whole area that surrounds the study area was reorganised by the government in a land consolidation project. After the land consolidation project groundwater levels dropped by 30 cm.

The *Juglans* trees at the orchard of Mr. Tuenter were planted at various well registered moments since 1895 (Table 43). J1895 is seedling of unknown origin seeded at this location in 1895. J1966 is a seedling originating from J1895 and was seeded at his location in 1966. J1976 is a *Juglans* of the variety Buccaneer, planted in 1976, when the tree was about 5 years old. The nut orchard also contains a *Juglans* planted in 2004 (Juglans regia, var. Broadview). This tree was ten years old when it was planted in 2004, because it was raised at another location. This tree is growing at a bare soil zone, just like the *Corylus* trees and was planted at a location that used to be *Corylus* orchard. This tree also receives fertilisation, in the form of animal manure. These conditions are all very different from the other Juglans trees at the orchard, so this tree was considered not to be representative and was left out of the research.

Table 43 Previous land use of parcels.

Parcel	Remarks
J1966	At this location there has been an orchard since at least 1940. In 1980 at a distance of 6 m from the tree, a settling tank has been installed. The installation of this tank might has disturbed the natural conditions of the soil. The exact location is not known, but our sampling may have been affected by this.
J1976	There used to a pig pen (until 1960 or so) in the area where the *Juglans* was planted in 1976 (as a 5-year-old tree). The wrenching of the pigs will have disturbed the natural conditions of the soil. The exact location is not known, but our sampling may have been affected by this.
J1966, J1976 and GrNE	These three parcels more or less have a similar management history according to the memory of Mr. Tuenter; most of the time in the past decades these parcels were covered by grassland.
J1895 and GrS	These two parcels more or less have a similar history according to the memory of Mr. Tuenter. Both parcels have been grassland for as long as he knows.
Ar, C1993, C1995 and C2011	These three parcels more or less have a similar history according to the memory of Mr. Tuenter. All *Corylus* were planted at land which used to be cropland before planting and with a history comparable to parcel Ar. All these parcels, including Ar, were cropland for most of the times, although at intervals in the past century they have also been covered by grassland. C1993 is a parcel without clear boarders at the northeast side. For that reason, we made a distinction in two different areas. The area which is used for calculating the number of trees per square meter is the area as shown in Appendix A.1.
C2011	Before planting the *Corylus* in 2008 and 2009 (so two times) 1820 kg ha^{-1} lime was added at this cropland
GrS	Until 1990 this grassland was being grazed for 6 months a year with 3 to 4 standard cattle units (Dutch: grootvee eenheden, GVE). In addition to this grazing, a regular amount (specific values are absent) of chemical and animal fertilisers was applied on this grassland. Since 1990 only compost and lime are added on this grassland (the same amount as at the parcels with *Juglans* and *Corylus* trees).

In the years 1993 and 1994 the parcel C1993 was planted with various varieties of *Corylus Avellana*. All Corylus at the orchard are inoculated at *Corylus Avellana* rootstocks. Next in the years 1995 and 1996 parcel C1995 was planted with various varieties of *Corylus*. In 2011 parcel C2011 was planted with *Colylus*. C2011 suffered numerous plagues of the larva of May-beetle, which led to the death of many trees that were replanted in the following years. Before planting *Corylus*, all soils were cultivated to a depth of 90 cm.

When analysing the historic maps of the region (Kadaster, n.d.), we saw most of Mr. Tuenter his comments confirmed.

Land use management

The complete orchard is managed organically, without the use of pesticides of chemical fertilisers. Some of the control parcels are managed traditionally (Table 44). A limited amount of animal manure and chalk (eggshells) is being applied. At the *Corylus* orchard, until t = 18, 18 m^3 ha^{-1} of manure is applied each year, after t = 18 this is reduced to 12 m^3 ha^{-1}. At the *Corylus* parcels, manure is only applied at the bare soil zone (not at the grassland). At the GrNE and Ar parcels, lime is applied every five years and the orchard every six years (at all trees and at GrS). The compost heap is located on top of a concrete soil. Percolation water is transported back to the compost heap. Every sixth year the compost heap is removed and compost is spread full field over the whole orchard, including grassland GrS.

Table 44 Farming categories.

Parcel	Owner	Management	History
C1993, C1995, C2011, GrS and all *Juglans* trees	Mr. Harm Tuenter	Organic farming	
Ar	Mr. Wim Pennings	Conventional farming	
GrNE	Mr. Sander Brus	Conventional farming	In 10 years, it has been cropland for 2 years (barley), rest grass (grass age ± 5 years)

All Corylus were planted at a distance of 2.2 m within rows and 4.4 m between rows. The Corylus trees were planted on north-south oriented 2.2 m wide stripes of bare soil zones, with stripes of grassland located between them. In 2006 50% of all trees were removed in the parcels C1993 and C1995, by removing complete rows of trees (north-south oriented). In 2013 a systematic thinning was performed in C1995 by removing every second tree in the rows (removing east-west oriented lines of trees). This was followed by a systematic thinning in C1993, according to the same strategy as in C1995. Some extra trees were removed in C1993 and C1995 as a pilot, though this felling-1 in 4 trees thinning remained a pilot. As a result of these thinnings, trees in C1993 and C1995 are now at a distance of 4.4m in the row and 8.8m between the rows, with a stripe of grass between of about 6.6m wide. This means that at the start 25% of the soil was covered by grass and after the second thinning 50% of the soil is covered by grass.

Cut wood and branches (prunings) are composted or burned and roots are chopped with a mulcher and left in the soil. All annual prunings with a diameter lower than 5 cm are composted (app. half of the volume, *Corylus*: 50% of 600 kg ha^{-1} yr^{-1}) and the rest is burned as firewood. The wood produced by thinnings every few years is turned into firewood.

The bare soil zone is kept bare by mechanical cultivation and weed torching. Half of the time, cuttings from the grassland in the orchard are left on the spot. The rest of the grass cuttings are composted. This applies to the grassland between the rows of *Corylus* and all other grassland at the orchard.

All leaves and husks are spread over the bare soil zone until the end of the winter, when they are transported to the compost heap. The amount of decried fruits is equivalent to 5% of the total harvest. Decried fruits are composted too. From the nut harvest, 50% is sold unpeeled and 50% is sold peeled. All unsold shells are composted at the orchard. 50% of a nut is shell and 50% is fruit (for both *Juglans* and *Corylus*). After drying the fruits, 15% of the weight has been lost.

Most of the management data collected by interviewing the owners was directly integrated in the Results spreadsheet.

Mr. Tuenter also provided us with the soil sampling data gathered at C1993 at February 2 1997 and January 2 1999 and at C1995 January 2 1999. The samples of 1999 might have been sampled slightly less deep than the samples of 1997.

To collect additional information on the vitality of the *Corylus* trees, leaf samples of trees in C1995 were sampled and analysed in a laboratory. Some of the results of these leaf sample analysis are a little below normal value, but not much. Most of the rest of the data is normal.

Appendix B Method

Appendix B.1 Method: Soil sampling

Within our study area, three types area characteristics can be distinguished:

A. Homogeneous parcels: cropland
B. Small homogeneous parcels: grassland
C. Stripe based heterogeneous parcels: *Corylus*
D. Individual tree based heterogeneous parcels: *Juglans*

Each type of area required another sampling method. For all tree covered parcels the sampling method is based on the idea that tree crowns and roots expand gradually, starting at the stem.

All soil samples were composite samples (FAO, 2019a); generated by mixing multiple samples (sometimes a composition of multiple composed samples) into a so called replica. On the recommendation of FAO (2019a), we examined SOC at a depth of 0-30 cm. Nair (2012) emphasises the importance of sampling beyond that depth when considered agroforestry systems (AFS). Therefore, we decided to include SOC at a depth of 30-60 cm into our sampling and take at least one sample at each study unit at a depth of 30-60 cm too. All soil samples in the 30-60 cm zone were composed by mixing the soil of two samples taken with and hand auger. Soil sampling for the 0-30 cm is elaborated in the next paragraphs.

Cropland
All soil samples in the 0-30 cm zone at the cropland (Ar-parcel) were composed of 40 gouge cores punctured randomly over the field, but at a minimum distance of 20 m from neighbouring allotments.

Grassland
All soil samples in the 0-30 cm zone at the GrS parcel were composed of 40 gouge cores centred around an area of 1 m^2 in the middle of the parcel. The limited size of the parcel made it impossible to apply the same method as applied at the Ar-parcel.

The soil sample in the 0-30 cm zone at the GrNE-parcel was composed of a mixture of two cores taken with a hand auger.

Corylus
At the *Corylus* orchards we applied a sampling method largely similar to the sampling method of Cardinael et al. (2017) and Lu et al. (2015). We distinguished three strata in the Corylus orchards (Figure 13):

1. Tree rows above bare soil;
2. Grass in the alley between the tree rows;
3. Grass at the location where a tree row was replaced by grass.

A parcel of *Corylus* contains multiple varieties of trees, though soil samples were gathered at a limited amount of locations. To rule out most of the potential influences of tree varieties on sampling data, all sampling was done at locations with a representative *Corylus* variety: Gunslebert. The growing speed of Gunslebert is supposed to be similar to the mean of all varieties.

All soil samples in the 0-30 cm zone of *Corylus* were composited by mixing 4 composed samples into a replica. At each sampling point ten gouge cores were punctured in a square area of 1 m^2 around the points S1.1, S1.2, S1.3 and S1.4 (Figure 13). For point S2 and S3 the same method was applied.

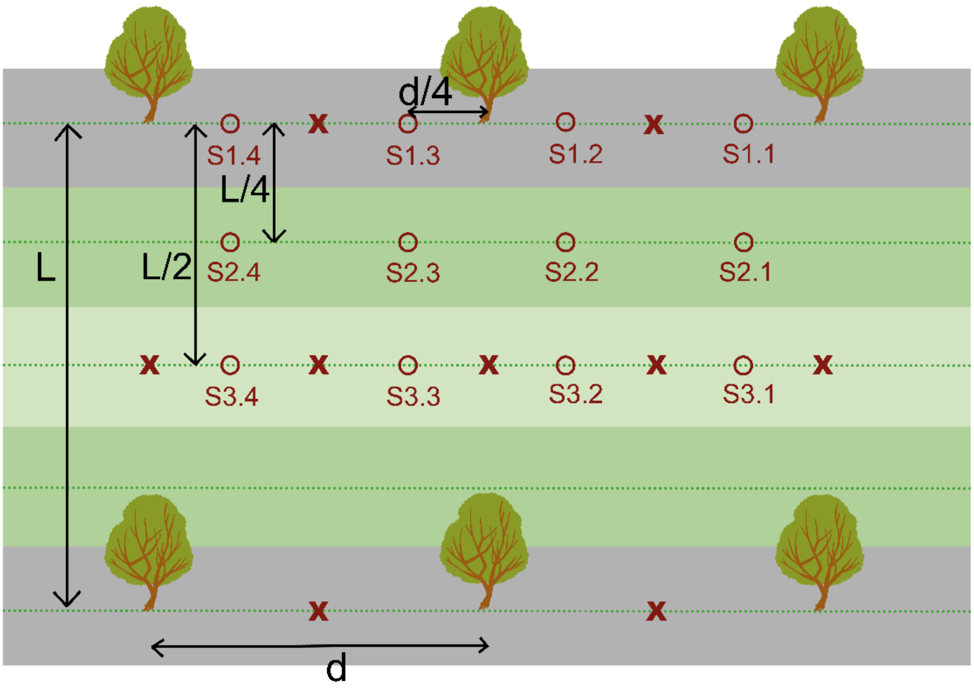


Figure 13 Soil sample distribution within Corylus parcels (o = sample locations, x = cut trees, L = 8.8 m, d = 4,4 m, grey = bare soil zone, dark green = grassland, light green = grassland/former bare soil zone, all samples with the same number before the point were turned into a mixed sample.

Juglans

All soil samples in the 0-30 cm zone of *Juglans* were composited by mixing approximately 4 composed samples into a replica. At the *Juglans* parcels we sampled at different distances from the heart of stem (Figure 14). The argument for doing this was that based on research of Pardon et al. (2017); Thevathasan and Gordon (2004) we expected a gradual decrease of OM and C in the soil, further away from the stem. This can be explained by a longer exposure of the soil to roots and litter, close to the stem.

Each sample was composed by mixing four soil samples taken at one distance from the tree; north, east, south and west from the tree. Ten gouge cores which were punctured in the square area of 1 m^2 around the points located 1.5, 3.0, 4.5, resp. 6.0 meters to the north, east, south and west from each tree (Figure 14). The sample taken at 1.5 m is considered to be representative for the area from the centre of the tree until halfway between 3.0 and 1.5 m from the stem. The sample taken at 3.0 m is considered to be representative for the circle at a distance halfway between 4.5 and 3 m, minus the first circle etc (Appendix B.2; Table 45).

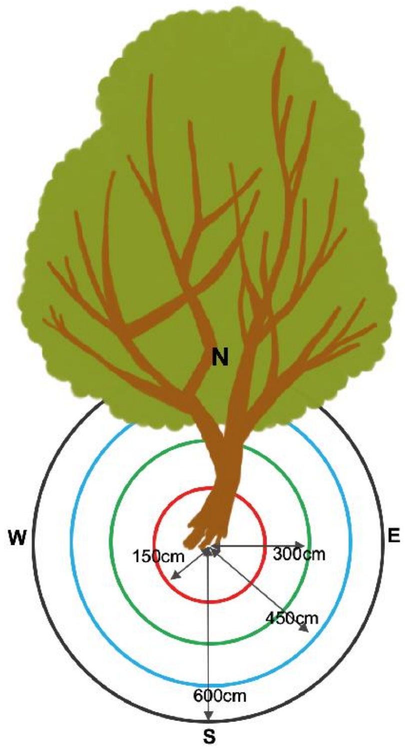


Figure 14 Soil sample distribution within Juglans parcels (at each circle four samples were taken in N, E, S, resp. W-direction and turned into a mixed sample).

Weights

The soil was sampled at individual points, so the point data had to be scaled into area data. This is easy for homogeneous parcels, however for all samples from parcels with trees had to be granted a specific weight, to take into inter-parcel spatio variety into account. All samples from parcels covered by tree were granted a weight (Table 45).

Table 45 Sample weights (At some of the sample locations an extra sample was taken, which initiated us to further adjust the weight for the specific sample).

Sample	Area	Sample weights
C2011S1, 2 & 3	50% bare soil (S1 & S3), 50% grassland (S3)	S1=25%, S2=50%, S3=25%
C1995S1, 2 & 3	25% bare soil (S1), 50% grassland (S2), 25% grassland that used to be bare soil (25%)	S1=25%, S2=50%, S3=25%
C1993S1, 2 &3	25% bare soil (S1), 50% grassland (S2), 25% grassland that used to be bare soil (25%)	S1=25%, S2=50%, S3=25%
J1976-1.5m	2.25*2.25*3.14 (radius^2*π) *100 trees	0.159
J1976-3.0m	3.75*3.75*3.14 (radius^2*π) *100 trees	0.283
J1976-4.5m	4.50*4.50*3.14 (radius^2*π) *100 trees	0.424
J1976-6.0m	Rest of parcel	0.135
J1966-1.5m	2.25*2.25*3.14 (radius^2*π) *100 trees	0.159
J1966-3.0m	3.75*3.75*3.14 (radius^2*π) *100 trees	0.283
J1966-4.5m	4.50*4.50*3.14 (radius^2*π) *100 trees	0.424
J1966-6.0m	Rest of parcel	0.135
J1895-1.5m	2.25*2.25*3.14 (radius^2*π) *70 trees	0.111
J1895-3.0m	3.75*3.75*3.14 (radius^2*π) *70 trees	0.198
J1895-4.5m	4.50*4.50*3.14 (radius^2*π) *70 trees	0.297
J1895-6.0m	Rest of parcel	0.394

Appendix B.2 Method: Biomass stock calculation

Corylus and *Juglans*

For the conversion of fresh *Corylus* and *Juglans* biomass to dry biomass, the fresh matter weight was multiplied with the mean moisture content, based on the data of Paul et al. (2017):

$$DM_{type} = FM_{type} * (1 - m) \quad (8)$$

Where:

DM_{type}= dry matter weight of a specific type of biomass (Mg DM ha^{-1})

FM_{type}= fresh matter weight of a specific type of biomass (Mg FM ha^{-1})

m= moisture content (0.4128 for *Corylus* and *Juglans* Paul et al. (2017), 0.83 for grass Eurofins (n.d.) and 0.908 for bovine slurry CDM (2017))

Corylus

Parcels C1993 and C1995

At several moments a part of the *Corylus* trees were removed by a systematic thinning. During this thinning, a specific percentage of the trees is cut, so the wood volume at the moment before thinning is:

$$FM_{tot\_trees} = FM_{thin} * (\frac{100}{p_{thin}}) \quad (9)$$

Where:

FM_{tot_trees}= total weight of fresh matter (FM) in trees (Mg ha^{-1})

FM_{thin}= harvested (thinned) FM (Mg ha^{-1})

p_{thin}= percentage of trees removed

For determining the mean diameter, we also involved trees which were outside (to the east) of the area as shown in Appendix A.1, which have the same management history and growing conditions. These trees outside the drawn area had almost exactly the same diameter as the mean, so this has had no effect on the average diameter. To calculate the current wood volume, one of the trees was measured in a destructive way in the winter of 2018/2019 by felling and weighted a model tree. The diameter of the model tree, was 25.15 cm. The mean diameter of the *Corylus* trees in C1993 was 22.71 cm and in C1995 was 23.29 cm. The FM mass is directly related to the volume, which is three-dimensional. For a volume it is not possible to use the diameter-ratio to calculate the volume of trees with another diameter.

For the conversion of these values, the following equation was applied:

$$FM_{mean\_parcel} = \frac{FM_{ref\_mean\_parcel}}{FM_{ref\_model}} * FM_{model} \quad (10)$$

Where,

FM_{mean_parcel} = weight of FM in mean tree of a parcel (Mg FM $tree^{-1}$)

FM_{model} = weight of FM in model tree (Mg FM tree^{-1})

$FM_{ref\_mean\_parcel}$ = weight of FM in reference tree of a parcel (Mg FM tree^{-1})

FM_{ref_model} = weight of FM in reference tree of model tree (Mg FM tree^{-1})

The reference FM of above ground biomass of *Corylus* trees at C1993 and C1995 is directly related to the diameter breast height (He et al., 2018):

$$FM_{ref} = 0.0156DBH^{1.974} + 0.0041DBH^{3.063} + 0.0861DBH^{2.381} \quad (11)$$

Where:

FM_{ref} = mass of AGB (kg FM tree^{-1})

DBH = diameter breast height

This equation refers to *Juglans* instead of *Corylus.* We chose to do so, because no such equation could be found for *Corylus* without 'h' as one of the parameters. We had no data on the height of our model tree. It is not clear if biomass in the equations of He et al. (2018) refers to fresh or dry matter (DM). We assume it to be fresh and applied a conversion to DM. If the equations of He et al. (2018) has DM as an output, than our values will be an underestimation of the real values.

The weighting of the model tree only involved stem and branches. To calculate the share of foliage, we based our calculations on the foliage share of AGB of *Juglans* (He et al., 2018; H. Zhang et al., 2017) and *Populus* (Borden et al., 2014) (Appendix B.2 *Table 46*), because we couldn't find such data in literature for *Corylus*. The mean share of foliage is based on 3 different reference values:

$$bc_{Corylus\_mean} = \frac{(bc_{lit\_1} + bc_{lit\_2} + bc_{lit\_3})}{3} \quad (12)$$

Where,

$bc_{Corylus\_mean}$ = mean content of foliage relative to the AGB (C %)

$bc_{lit\_\#}$ = content of foliage relative to the AGB according to source # (C %)

Foliage weight was only calculated for the current C-stock in the *Corylus* trees. In all calculations for past prunings and thinnings in C1993 and C1995, C-stock was based at branches and stems.

Parcel C2011

The DM weight of AGB of the trees at C2011 is directly related to tree height and diameter breast height (Albert et al., 2014):

$$DM_{AGB-tree} = a * h * DBH^2 + b \quad (13)$$

Where,

$DM_{AGB-tree}$ = mass of AGB (kg DM tree^{-1})

a = 0.0364 (SE=0.0011)

b = 0.0308 (SE=0.0032)

h = tree height (m)

DBH = diameter breast height (cm)

Remark: DBH is not really an DBH for the *Corylus* in C2011, because the DBH was determined at the thinnest point of the stem below the lowest branches, because branches were located lower than DBH. This can be the source of a slight overestimation of the AGB. The equation of Albert et al. (2014) is for dry wood. To convert dry biomass to, fresh biomass, the outcome was multiplied by 100/50, because fresh biomass contains 50% of water.

The BGB C-stock of *Corylus* is directly related to the AGB C-stock and tree age (Cairns et al., 1997):

$$Cstock_{BGB-tree} = e^{-1.3267+0.8877xln(Cstock_{AGB-tree})+0.1045xln(Age)} \quad (14)$$

Where,

$Cstock_{BGB\text{-}tree}$ = mass of BGB (Mg C ha^{-1})

$Cstock_{AGB\text{-}tree}$ = aboveground biomass (Mg C ha^{-1})

Age = number of years since planting (years)

Juglans

The Juglans trees of study are not situated at a complete *Juglans* orchard. To scale up data from solitary trees to values of C per hectare, we needed to find how much *Juglans* trees are normally planted at one hectare. Wertheim (1981), Thevathasan and Gordon (2004) and Cardinael et al. (2017) all mention various planting distances, from below to over 100 ha^{-1}. The research of Borden et al. (2014) and Wotherspoon et al. (2014) is based at orchards with 111 *Juglans* trees per hectare. J1966 and J1976 both have a crown diameter close to 10m, we therefore based our calculations at a stem number of 100 trees ha^{-1}. J1895 on the other hand is a very large tree, with a crown diameter of 15.5m. For this tree we choose to calculate with a stem number of 70 trees ha^{-1}, since J1895 could not have developed such an extended crown if planted at 100 stems per hectare. Trees planted at a density of 70 trees ha^{-1}, will have plenty of space to grow for most of the time.

For determining the *Juglans* biomass it was not possible to do exact measuring by cutting down trees. Therefore, data from literature had to be used to determine aboveground biomass (AGB) and belowground biomass (BGB) (*Table 46*).

According to Nilsson and Schopfhauser (1995) the ratio between AGB and BGB is expected to be stable over the years. Therefore, one AGB-BGB-ratio was applied at all *Juglans* trees. He et al. (2018) provides us with allometric equations for determining biomass with just the input of the DBH. Nilsson and Schopfhauser (1995) and H. Zhang et al. (2017) do not provide us with this kind of allometric equations, so we chose to use the equations of He et al. (2018) to calculate AGB and coarse roots.

For calculating fine roots we deduct the 26.7% (H. Zhang et al., 2017) with 25.0% (He et al., 2018), which results in 1.7% of the weight of AGB for the fine roots. We choose to use the values of H. Zhang et al. (2017) above Nilsson and Schopfhauser (1995) because the former is about *Juglans* regia and the latter is a global average of all trees in forest, so the number of H. Zhang et al. (2017) is less contaminated with other tree and shrub species.

Table 46 Biomass shares of various parts of Juglans trees (Data show C-concentration, except He et al. 2018) which shows biomass concentration. Numbers between brackets are kg/tree for He et al. (2018) and Mg ha-1 for H. Zhang et al. (2017). Above Ground Biomass = AGB and Below Ground Biomass = BGB).

Parameter	**He et al. (2018)**	**H. Zhang et al. (2017)**	**Nilsson and Schopfhauser (1995)**	**Thevathasan and Gordon (2004)**
Tree species	*Juglans mandshurica*	*Juglans regia* (13 yr)	Various (a global mean)	*Populus* sp. (13 yr)
Foliage (% of AGB)	3.1% (10.4 ± 10.7)	12.6% (2.28 ± 0.24)		10.15% (11.7 ± 3.5)
Branches (% of AGB)	33.7% (114.5 ± 148.3)	36.3% (6.57 ± 1.54)		42.76% (49.3 ± 25.8)
Stem (% of AGB)	63.2% (214.3 ± 179.0)	51.1% (9.25 ± 1.95)		47.09% (54.3 ± 33.5)
Coarse root (% of AGB)	25.0% (84.9 ± 86.8)			
BGB (coarse and fine roots) (% of AGB)		26.7% (5.63 ± 1.19)	25%	

To calculate the share of foliage, branches and stems in *Juglans* we calculated with the mean of He et al. (2018) and H. Zhang et al. (2017), because both research results have their advantages. The former has involved older trees then the latter and the latter is about the same tree species as the type of *Juglans* in our parcels J1895, J1966 and J1976.

We compared the output of the equation of He et al. (2018) with a smartphone-app of Thomassen (n.d.), which uses equations of Dik (1996) as a basis. The results of these calculations were in line with the output of He et al (2018).

The amount of FM in AGB of *Juglans* trees is directly related to the diameter breast height (He et al., 2018):

$$FM_{AGB-tree} = 0.0156DBH^{1.974} + 0.0041DBH^{3.063} + 0.0861DBH^{2.381} \quad (15)$$

Where:

$FM_{AGB\text{-}tree}$ = mass of AGB (kg tree-1)

DBH = diameter breast height

It is not clear if biomass in the equations of He et al. (2018) refers to fresh or dry matter (DM). We assume it to be fresh and applied a conversion to DM. If the equations of He et al. (2018) has DM as an output, than our values will be an underestimation of the real values.

The amount of FM in coarse roots of *Juglans* trees is directly related to the diameter breast height (He et al., 2018):

$$FM_{BGB-coarse} = 0.0166DBH^{2.565} \quad (16)$$

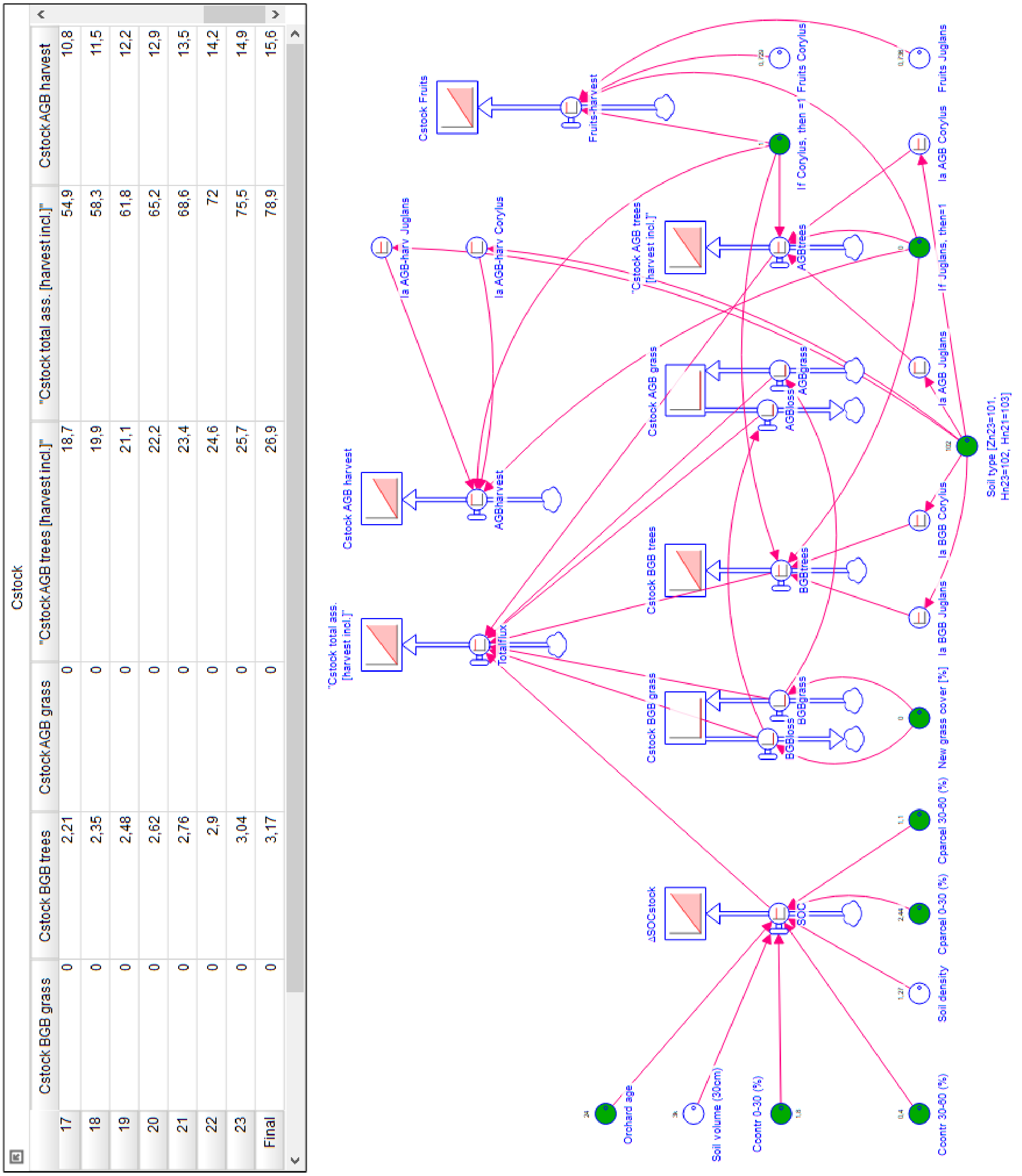
Where:

$FM_{BGB\text{-}coarse}$ = mass of fresh matter in coarse roots (kg tree^{-1})

DBH = diameter breast height (cm)

Appendix B.3 Method: Model

The model was built with Stella software (Figure 15).



Cstock

	Cstock BGB grass	Cstock BGB trees	Cstock AGB grass	"Cstock AGB trees [harvest incl.]"	"Cstock total ass. [harvest incl.]"	Cstock AGB harvest
17	0	2,21	0	18,7	54,9	10,8
18	0	2,35	0	19,9	58,3	11,5
19	0	2,48	0	21,1	61,8	12,2
20	0	2,62	0	22,2	65,2	12,9
21	0	2,76	0	23,4	68,6	13,5
22	0	2,9	0	24,6	72	14,2
23	0	3,04	0	25,7	75,5	14,9
Final	0	3,17	0	26,9	78,9	15,6

Figure 15 CANOE model to model future pathways of C-sequestration (all units in Mg C ha-1. All green cells have to be checked and adjusted for each parcel for which the model is used). The model is only suitable to be used for nut orchards at sandy soils in the temperate climate zone of the Netherlands.

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Appendix C Results

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Appendix C.1 Results: Sample overvie

The locations at which the sampling took place can be found on the map in Appendix A.4. A complementary description is given for *Corylus* parcels by pointed out in which tree row and between which trees sampling took place (counted from the south, all replaced trees excluded) (Table 47).

Table 47 Identification of the chronosequences, parcels and samples.

Parcel code	Parcel area (m^2)	Chrono-sequence	Main vegetation	Location	Soil description	Soil samples codes	Earthworms sample
Ar	37079	C-loamy hydro	None/maize	Randomly spread at the whole parcel, except at the 15 m zone next to the surrounding trees	G5	A1, A2	AE
GrNE	6821	C-loamy brown, J-loamy	grass	See map in Appendix A.4	G6, G7	GrNO1	none
GrS	1137	J-sandy	grass	See map in Appendix A.4	G13	GrS1, GrS2	Grs2
GrW	35079	none	grass	See map in Appendix A.4	G4	none	none
C1993	17792	C-loamy hydro	*Corylus* 1993/ 1994	Row 5 and between row 5 and 6, from tree 19 to 21	G1, G2, G3, G8	Ca1, Ca2, C1993-S1, C1993-S2, C1993-S3,	C1993-S2
C1995	10007	C-loamy brown	*Corylus* 1995/ 1996	Row 3 and between row 3 and 4, from tree 5 to 7	G10	Cv, C1995-S1, C1995-S2, C1995-S3	C1995-S2
C2011	19539	C-loamy hydro	*Corylus* 2011	Row 9 and between row 9 and 10, from trees 36 to 40	G9	C2011-S1, C2011-S2, C2011-S3	C2011-S2
J1895	143	J-sandy	*Juglans* 1895		G14	J1895-w1,5, J1895-w3,0, J1895-w4,5, J1895-w6,0	J1895-w3,0
J1966	100	J-loamy	*Juglans* 1966		G11	J1966-w1,5, J1966-w3,0, J1966-w4,5, J1966-w6,0	none
J1976	100	J-loamy	*Juglans* 1976		G12	J1976-w1,5, J1976-w3,0, J1976-w4,5, J1976-w6,0	none

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Appendix C.2 Results: Physical quantities

For good comparison it is best to take all samples at the same time. We decided to take samples in different series. The motivation to do so was that budget was limited and waiting for results before collecting the next set of samples gave us the opportunity to adjust our sampling method if unusual results would appear. The results were not unusual though, so sampling was continued in the same way as originally programmed.

In the winter of 2018/2019 three sets of soil samples were collected: on November 21 2018, February 14 2019 and April 24 2019. All raw soil data can be found in Appendix C.5 (*Table 54*) and Table 48 shows additional information about our the structure sub-maps in our Excel-file.

Table 48 Types of data and data description of different sub tables.

Tab	Type of data described in the tab	Comment	Date of data collection
TOT_main table	Data of all other tabs combined in one spreadsheet	The columns contain information about the different parcels, subdivided into different parts of the parcels, that are given different sample weights. The rows contain data about the different parcels, grouped into data types (soil lab, soil flux, biomass flux, soil inventory, soil & tree & biomass calculation)	Various
TOT_abstract	Abstract of TOT_main	A collection of the most important information of the TOT_main_table	Various
Parcels	A summary of the parcels and the age of the trees (year of reference= 2019)		Does Not Apply (DNA)
Soil_samp	Sampling number		See Tot_main_table
Earthworms	# and weight of earthworms at a depth of 0-30 and 30-60cm at various parcels	Weight loss factor has been added since, when the cups were weighted, approximately 20% of the weight of earthworms had appeared as faeces (weighting could only take place 24 hours after sampling, because a better balance had to be purchased)	April 19, 2019
Fl_compost	The amount of C in compost	This relates to fluxes	Jan-Apr 2019
Fl_manure	The amount of C in manure	This relates to fluxes	Jan-Apr 2019
Fl_crop	The amount of C in crops	This relates to fluxes	Jan-Apr 2019
Fl_thinning	The amount of wood that was removed by various thinnings. The wood volume of average *Corylus* trees	This relates to fluxes	Jan-Apr 2019
Fl_fruits	The amount of fruits harvested per tree, ha and year	Gunslebert, Gustav's Zeller and Cosford are *Corylus* varieties.	Jan-Apr 2019
Juglans area	For *Juglans* the samples were taken at a certain distance from the tree. This tab describes for what area these samples are representative.	The further away from the tree, the larger the area for which the sample is representative. J1895 is based on 70 trees ha^{-1}, the other *Juglans* on 100 tree ha^{-1}	DNA
Tree_total	All data about trees: number, Dbh, height, crown diameter. This tab also includes the calculations for fresh biomass of aboveground and belowground biomass for *Juglans*.	In this table the data about the trees of TR_C1993_iB and TR_C1995 and TR_C2011 are accumulated and complemented with data of the *Juglans* parcels.	Inventory of Juglans: March, April and June 2019

Tab	Type of data described in the tab	Comment	Date of data collection
TR_C1993_iB	The number and diameter of the *Corylus* trees in C1993	Including trees that are at the border of the parcel	Apr-May 2019
TR_C1993_eB	The number and diameter of the *Corylus* trees in C1993	Trees at the border excluded	Apr-May 2019
TR_C1995_iB	The number and diameter of the *Corylus* trees in C1993	Including trees that are at the border of the parcel	Apr-May 2019
TR_C1995_eB	The number and diameter of the *Corylus* trees in C1993	Trees at the border excluded	Apr-May 2019
TR_C2011	The number and diameter of the *Corylus* trees in C2011	Trees are too young to be significantly affected by neighbouring trees.	June 2019
Leafs_qual	Results from laboratory analysis	Only collected in C1995	August 15 2018
Grass	The amount of dry matter in grass		DNA
S_Bulk density	Bulk density of soil types	Including the sensitivity analysis	DNA
S_A-horizon	Boundary between A- and B-horizon	Including the sensitivity analysis	DNA
S_Chron_C1995	Variations in chronosequence composing	Including the sensitivity analysis	DNA
R_SOC_local	Results; spatial variety in SOC	Calculations	
R_SOC_S&F	Results; SOC-stock & SOC-flux	Calculations	
R_BGB_stock	BGB-C-stock	Calculations	
R_Wood	Wood-C-stock (current & harvested)	Calculations	
R_Stock_tot	Total C-stock	Calculations	
R_BGB_flux	BGB-C-fluxes	Calculations	
R_flux_tot	Total C-fluxes	Calculations	
R_qual	Quality scores	Calculations	
HWC_qual	Hot Water Carbon	Calculations	
Corylus	Tree diameter	Calculations to check tree diameters	
Foliage_%	Mass volume of types of tree biomass	Calculations to check share of leaves to biomass	

Earthworms

The type of species to which the collected worms belonged was not documented. Unfortunately, after 24 hours when the weighing took place, the earthworms were not very suitable anymore to be determined. Based on our observations the earthworms seemed to be belong to the three most common earthworm groups: 1. Epigeic worms (above the soil), 2 Endogeic (in the soil) and Anecic (vertical burrow builders).

Tree_total

To determine the height of trees, the height was measured 2 or four time per tree; in opposite directions. Heights were measured multiple times to filter out any side effects like slope. For C1993 and C1995 the height was measured of one tree in every row with a Dbh as close to the mean Dbh as possible. The height of trees in C2011 was measured of randomly chosen trees and was measured only once per tree, because the trees are still very small. Heights in the orange cells have been copied, to prevent that certain cultivars (which are relatively short) would have been over weighted. Some slow growing varieties where over represented in the measuring. All heights were measured with a Silva optical height meter (clinometer).

All diameters were measured with a flexible tape. The Dbh of the *Corylus* was calculated in two steps. Not all varieties contained the same number of trees in a row. To prevent the overweighing of a certain variety the next steps were proceeded:

1. Calculate the average Dbh of the trees in a row.
2. Calculate the average Dbh of the parcel.

Row 18 Crown (pruned away) is an estimated number to express what percentage of the tree has been pruned away in the lifetime of the tree. This was done to get an impression of the total wood production over the lifespan of the tree.

TR_C1993_iB, TR_C1993_eB, TR_C1995_iB, TR_C1995_eB

For calculating the mean diameter the following equation was used Bosschap (2002):

$$D_m = \sqrt{\frac{Sum(N * Dbh^2)}{N}} \qquad (34)$$

Where,

D_m = mean diameter

N = number of trees with a specific diameter

Dbh = diameter at breast height

The diameter at breast height (Dbh) is to be measured at 1,30m above the ground (Bosschap, 2002), though that is a protocol for trees in a forest. In a forest most of the times the lowest branches of trees are located many meters above the ground. In the nut orchard the branches of *Corylus* start as low as 1m above the ground. For *Corylus* therefore we decided to measure Dbh at the point below the lowest branch, were the stem is the thinnest.

In C1993 the number of trees was so large that we decided to measure fifty percent of the *Corylus*. The trees were measured in an alternating pattern. In row 32 is written down at which tree measuring was started. In C1995 all trees were measured.

The last column (cut tree) of C1993 shows the dimensions of the tree that was felled and weighted.

The rows which contain trees of the *Corylus* variety Gunslebert were marked green, because Gunslebert was the variety where soil samples have been analysed.

For C1993 and C1995 trees planted more than 20 years after the initial planting, were left out of the sample, to keep the data representative. Most of the trees that were left out, were planted last year or in recent years after the thinning, to replace dead trees. For C2011 trees planted more than 4 years after the initial planting are left out of the sampling.

For C1995, the first two rows were left out of the sample, because these rows are not representative for the rest of the parcel. These first two rows seemed to be too much influenced by side effects.

Appendix C.3 Results: Soil quality description

All soil quality descriptions in this appendix are based on single samples taken by hand auger or by digging soil pits. Locations at which the sampling took place can be found on the map in Appendix A.4 (Table 49, Table 50). A complementary description is given for *Corylus* parcels by pointed out in which tree row and between which trees sampling took place (counted from the south, all replaced trees excluded).

Table 49 Soil quality description (Sub tables G1 until G13)

C1993, row 8, between tree 15 and 16 (nr. G1)	**Pictures: 3117-3120 (May 1 2019)**
Depth (cm)	**Remark**
0-20	A-horizon (grey-brown)
20-33	A-horizon, colour a bit lighter than 0-20
33-50	Loamy, orange/yellow, oxidised, corridors with organic matter
50-65	Sandy
65-75	Reduced, still porous, corridors with old roots and rust
75	Groundwater level
75-	Completely oxidised, no activity

C1993, row 5, between tree 20 and 21 (nr. G2)	**Pictures: 3121-3122 (May 1 2019)**
Depth (cm)	**Remark**
0-30	A-horizon (grey-brown)
30	Clear demarcation
30-65	Oxidised sand, some corridors. Not loamy
65-80	Reduced, with some oxidised corridors
80	Groundwater level
80-	Completely oxidised, no activity

C1993, row 1, ca. betw. tree 20 and 21 (nr. G3)	**Pictures: 3123-3127 (May 1 2019)**
Depth (cm)	**Remark**
0-30	A-horizon (brown)
30-55	Orange-brown, oxidised sand, many corridors with organic matter and pores, a little loamy and some charcoal parts.
55-60	Orange, loamy, some charcoal parts,
60-85	Reduced sand, some roots, with some oxidised corridors, some charcoal parts
85	Groundwater level
85-	Completely oxidised, no activity, some charcoal parts, more grey-blueish than G1 and G2

Grassland W-(GrW) (G4)	**Pictures: 3128-3132 (May 1 2019)**
Depth (cm)	**Remark** (no loamy layer in G4, no stagnation)
0-15	A-horizon (light brown, sandy) More sandy than G1-G3, falls out of drill, less loamy
15-30	A little more sandy, light brown/orange-brown. 0-30 is very dry and contains a little charcoal
30-40	A little darker and loamier than 15-30
40-50	Orange-brown, oxidised sand, corridors with organic matter and pores and some charcoal parts
50-65	Pure sand, grey/orange, reduced sand with some oxidised corridors, some charcoal parts
65	Groundwater level
65-	All oxidised sand, some oxidised corridors, charcoal parts

The tendency from G1 to G4 is increasing sand shares and reducing loam shares.

Ar (nr. G5)	**Pictures: 3133-3137 (May 1 2019)**
Depth (cm)	**Remark**
0-33	A-horizon, loamy sand, orange/light brown
33-43	Gley, orange with a little grey, oxidised and reduced loamy sand next to each other, large corridors with organic matter and pores, some charcoal parts.
43-55	Even orange, loamy, some charcoal parts
55-66	Reduced sand, some roots, with some oxidised corridors, some charcoal parts
66	Groundwater level
66-	Completely oxidised sand, no loam, some gravel, no activity, some charcoal parts

GrNE nr. 1 (nr. G6)	**Pictures: 3148-3150 (May 1 2019)**
Depth (cm)	**Remark**
0-35	A-horizon, sandy, black
35	Clear demarcation
35-50	Grey sand with some oxidation (orange) corridors and some organic matter corridors. Well worked through by earthworms and many roots running through it. No charcoal at this location
50-80	Mostly reduced sand, some with some oxidised corridors (less organic matter than at 35-50 cm), gley
80	Groundwater level
80-	Completely oxidised sand, no loam, no activity

GrNE nr. 2 (nr. G7)	**Pictures: 3151-3153 (May 1 2019)**
Depth (cm)	**Remark**
0-38	A-horizon, sandy, black
38	Clear demarcation
38-65	With some oxidation (orange) corridors and some organic matter corridors, gley (grey and brown and orange). The orange colour is a bit deeper than at G6. Some charcoal at this location. With some gravel of about 9 mm.
65	Groundwater level
65-	Completely oxidised sand, no activity

C1993, row 6, between tree 18 and 19 -only mature trees counted- Soil pit (nr. G8)	**Pictures: 120030, 120043, 120055, 3156-3163 (May 16 2019)**
Depth (cm)	**Remark**
0-30	A-horizon, grey/blackish, this part certainly contains most of the roots, maybe 80% of the roots is horizontally orientated. One very large root just above the 30 cm border.
30-63	AC-horizon, dark brown, contains some humus, some loam, but not one special loam layer. Some roots and not a lot of biological activity, so we expect most of C-transport to take place by C-transport through channels instead of C-transport by decomposing small roots
63-73	Gley-zone, both grey (reduced) and orange (oxidised). Some roots and oxidised channels
73-	All grey, no roots
83 á 90	Groundwater level
In general	Hard soil, compact

C2011, row 10, between tree 55 and 56 -all trees counted, incl. empty spots- Soil pit (nr. G9)	**Pictures: 132945, 133010, 134005, 134014, 141728, 141734, 3164-3171 (May 16 2019)**
Depth (cm)	**Remark**
0-32	Light brown. The A-horizon seems to have more earthworm-activity than Haz. 1994. A few thick roots, many worm holes. Most roots in the A-horizon just above the 32 cm layer.
32-55	Gley-zone, mostly grey (reduced) and some orange (oxidised), with decreasing oxidation with larger depths. Some roots (much less than in the A-horizon) and oxidised channels. Coarse sand
55-	All grey, no roots. At 80 cm (just above groundwater) we found a nice fat earthworm (Anecic)
85 á 90	Groundwater level
In general	Roots smaller than under Haz 1994, much easier to dig a hole at this locations, much less dense, less compact and much more loose than the ground under Haz 1994. In the middle of this parcel the soil is more greyish and sandy than the northern part of C2011

C1995, row 7 (Cosfort), between tree 8 and 9 (nr. G10)	**Pictures: 145805, 145826, 145830, 145836, 3172-3178 (May 16 2019)**
Depth (cm)	**Remark**
0-50	Uniform black and crumbly
50-85	Worked/dug through, mixture of brown, yellowish and black ground, roots
85-110	Greyish/black, some roots until 1 m depth,
110-	Light grey, fully reduced
In general	'esgrond'. Nice loose and crumbly ground.

J1966, 2,4m SE from stem (nr. G11)	**Pictures: 3179-3180 (May 16 2019)**
Depth (cm)	**Remark**
0-40	Black crumbly soil, well rooted through, quite dry (almost falls out of the soil auger)
40-60	Black crumbly soil, well rooted through
60-70	Yellow/orange sand with some humus corridors (rinsed in from above)
70-78	Grey-brown with black corridors and some roots, some charcoal, some gravel (16 mm)
78-90	Light grey/yellowish.
90-105	All grey, coarse sand
105	Groundwater
105-110	All grey, very wet coarse sand with some gravel (15 mm)

J1976, 2,1m ESE from stem (nr. G12)	**Pictures: 3181-3187 (May 16 2019)**
Depth (cm)	**Remark**
0-30	Grey-brown fine sand (looks finer than the sand from the top layer of Wal 1966)
30-55	Mostly oxidised sand with some light-yellow spots and some strong oxidised spots/channels, living roots and dead roots (up to Ø 6 mm), some loam in it, the deeper I drill in this layer, the loamier it seems to get,
55-75	Gley zone, orange loamy sand with a grey taint, grey and orange in corridors and spots next to each other. Mixture of oxidation and reduction with some thin living roots
75-88	Grey, slightly coarse sand with orange (oxidised) corridors and some roots
88-95	Same as 75-88, but the grey colour is more intense
95	Groundwater
95-100>	Completely grey coarse sand with large parts of dead wood (Ø<25mm), maybe old roots or an old pole, some clots of loam, some corridors of oxidation
In general	Over all much lighter of colour than Wal1966

J1895, 3,0m SE from stem (G14)	**Pictures:3233-3235**
Depth (cm)	**Remark**
0-30	Grey-black fine sand. A slight grey taint, well crumbly
30-55	Brown-black fine sand. Well crumbly.
55-60	Red-brownish, lots of oxidisation, small pieces of iron ('oer')
In general	No gravel or charcoal. At 60 cm a solid layer of iron makes it impossible to drill any deeper

Weide 2 (G13)	**Pictures:3236-3239**
Depth (cm)	**Remark**
0-30	Very fine brown/dark grey sand. The soil is so dry and limeless that it falls out of the auger.
30-50	Light-grey sand with brown and black corridors.
50-70	Dark yellow/brownish sand. Fine living roots. Oxidised.
70-	A solid layer of iron which makes it impossible to drill any deeper

Table 50 Distribution of soil descriptions over the parcels.

Parcel-code	**Chronosequence**	**Soil description**	**Boundary of A-Horizon (cm)**
Ar	C-loamy hydro	G5	33
C2011	C-loamy hydro	G9	32
C1993	C-loamy hydro	G1, G2, G3, G8	30
GrS	J-sandy	G13	30
J1895	J-sandy	G14	Not clear
GrNE	C-loamy brown, J-loamy	G6, G7	35
J1976	J-loamy	G12	35
J1966	J-loamy	G11	Not clear
C1995	C-loamy brown	G10	42.5

In *Table 39* all information on A-Horizons is combined into one value for each parcel.

Appendix C.4 Results: Additional data description

A description of the main details of our raw data (Appendix C.5; *Table 54*) can be found in Table 51. This appendix also summarizes some additional results.

Chronosequence

The lowest values for carbon and SOM were found in the parcels Ar (1.4%), C1993 and C2011, with the highest values in C1993 (1.53 %), which is the one which has been covered with trees for the longest period of time (Table 51). Soil quality of these parcels, as described in Appendix C.3, also shows many similarities, and so do C/N and C/S ratios, S-stock, water retention curve and the clay fraction. These three parcels have a similar management history (Appendix A.5), so they were grouped to one chronosequence.

The next group of parcels with largely similar data values and a comparable management history were the parcels GrNE, J1966, J1976 and C1995. The amount of C in the top 30 cm for instance lies between 1.8% and 2.53%. Soil quality of these parcels, as described in Appendix C.3, also shows many similarities, and so do the clay, silt and sand fractions. The S-stock, water retention curve and C/N and C/S ratios show some variation between the different parcels. These parcels contain different types of nut trees, and therefore we decided to split this group into two different chronosequences.

The last group of parcels which was combined int a chronosequence were the parcels GrS and J1895. The management history of these two parcels has a large resemblance, and so do the amounts of C and SOM, the C/N ratio and the description of the soil quality and the clay, silt and sand fractions.

Soil data results from laboratory analysis

The soil sampling data gathered at C1993 at February 2 1997 and January 2 1999 show a remarkable drop in SOM and enormous increase of pH. Analysis in 1997 was performed by Bedrijfslaboratorium Oosterbeek and analysis in 1999 was performed by Gaia Bodemonderzoek. The exact methods of analysis of both institutions could not be recovered. One possible explanation for the large spread in values, is a different way of sampling or processing. Therefore, we choose not to include the data collected in 1997 and 1999 in our analysis.

Sample GrS1 was collected at a location in the grassland that has been cultivated and reseeded after a plague of grubs a few years ago. Sample GrS2 was collected at an undisturbed part of the grassland. Cultivating a soil is known for stimulation of respiration of SOM and C. This might be an explanation why carbon and SOM values of GrS1 are lower than GrS2.

Earthworms

The share of large worms was not documented, but based on our observations, we can say that the share of large (anecic) worms seemed to be constant for all parcels that had trees and or grass on it. The cropland had relatively few large worms. The bottom of the sample block seemed to have no vertical burrows, although all *Corylus* trees had many ends of anecic worm burrows around their stem. So, either the large worms do no stay at a depth of more than 30cm, or the large worms were not stimulated to appear after applying the mustard-water-solution.

Table 51 Result details per parameter.

Code	Parameter	Comments
L05	C-organic (0-30cm)	Lowest values: Ar, C2011 and C1993. Highest values: GrS, J1966 and J1895
L06	C-org. (30-60cm)	Lowest values: Ar, C2011 and GrNE. Highest values: GrS, J1966 and J1895
L07	Org (SOM) (0-30cm)	Lowest values: Ar, C2011, C1993 and GrNE. Highest: GrS, J1966 and J1895
L08	Org (SOM) (30-60cm)	Lowest values: C2011 and GrNE. Highest: GrS, J1966 and J1895
L09	C/SOM (0-30cm)	The ratio is more or less the same for all parcels, though the highest values can be found in the soil of parcels that have been undisturbed for the longest time.
L10	C/SOM (30-60cm)	Lowest values: Ar, C2011 and C1993 (all the same type of soil). Highest: GrS, J1895 and J1966.
L11	N-stock	Lowest values: C1995, Ar and C2011. Highest: J1976, GrS and J1895
L12	C/N	Highest in GrS, J1895, J1966, C1995. (the fewer disturbance, the higher C/N)
L13	N-delivery cap.	Lowest C1995 and J1966. Highest C2011, C1993, GrS and GrNE
L15	S-available	Lowest: C1993, J1895 and C1995. Highest: GrNE
L16	S-stock	Lowest: Ar, C2011 and C1995. Highest: J1976 and J1895
L17	C/S	Lowest: GrNE, Ar, C2011. Highest: J1966, C1995 and GrS
L18	S-delivery cap.	Lowest: Gr Sand C1995. Highest: GrNE, J1976 and J1895
L20	P (available)	Lowest: Ar and GrS. Highest: C1993 and C1995
L21	P (stock)	Lowest: Ar, C2011 and J1976. Highest: GrNE, C1993 and C1995
L22	K (available)	Lowest: Ar and GrNE. Highest: C2011, C1993, J1976
L23	K (stock)	Lowest: GrS and J1895. Highest: Ar, C2011 and C1993. Ar has a high stock, but low availability.
L26	Ca (available)	Lowest: Gr Sand J1895. Highest: C2011, C1993 and J1966
L27	Ca (stock)	Lowest: C2011, GrNE and J1966. Highest: C1993 and J1895. J1895 has the highest stock, but the lowest availability
L28	Mg (available)	Lowest: C2011, Gr Sand J1966. Highest: C1993 and GrNE
L29	Mg (stock)	Lowest: J1966 and C1995. Highest: J1895 has a low availability and a high stock
L31	Na (available)	Lowest: C2011 and GrS. Highest: GrNE (due to large manure application?)
L32	Na (stock)	Lowest: C1993 and C1995. Highest: Gr Sand J1895 (small spread)
L33	pH	Lowest: Gr Sand J1966. Highest: C1993, GrNE and C1995
L35	Clay	Ar, C2011 and C1993 have a high % of clay.
L36	Silt	Lowest: J1895. Highest: Ar
L37	Sand	Lowest: Ar
L38	Clay-humus	Lowest: C2011, GrNE and J1966. Highest: C1993, J1895, J1976 and C1995. The longer covered by trees, the higher the clay-humus-%.
L39	CEC-occupation	Lowest: C2011 and GrS. Highest: C1993, J1895, GrNE and C1995. The longer covered by trees, the higher the CEC.
L40	Ca-occupation	Lowest: C2011 and GrS. Highest: C1993, J1895 and C1995. The longer covered by trees, the higher the Ca-occupation
L41	Mg-occupation	Lowest: C1993, C1995, J1976 and J1966. Highest:C2011 and GrNE
L42	K-occupation	Lowest: C1993, GrS, J1895, J1976 and C1995. Highest: Ar, C2011 and J1966
L43	Na-occupation	Lowest: C1993, J1976 and C1995. Highest: GrS and J1966
L44	H-occupation	Lowest: C1993, C1995, J1895 and GrNE. Highest: GrS, J1966
L45	Al-occupation	Highest: Gr Sand J1966
L46	Crumble capacity	Lowest: Ar, C2011 and C1993. The more clay, the lower the crumble capacity.
L47	Soil crusting	Lowest: Ar. Highest: GrS, S1895, J1976 and C1995
L48	Moisture retaining cap.	Lowest: C2011 and J1895. Highest: J1976, J1966 and GrS
L49	Micro-biol.-activity	Lowest: Ar, C2011 and C1993. Highest: GrS, GrNE, J1976 and J1895. The more clay, the lower the activity
L51	SOM annual breakdown	Lowest: GrS, J1895 and C1995. Highest: Ar, C2011, C1993and GrNE. The longer covered by trees, the lower the annual OM breakdown.
L52	SOM quality	Lowest: Ar, C2011 and GrNE. Highest: J1895, J1966. The longer covered by trees, the better the quality of the OM
L53	Soil structure	Lowest: Ar, C2011, GrS. GrNE and J1966. Highest: C1993, J1895, J1976 and C1995. The longer covered by trees, the better the quality of the OM
L54	Texture	Loamy: Ar, C2011 and C1993. Sand: GrNE and J1895. Rest is loamy sand/sand
L55	Water retent. Curve	Lowest: C1995. Highest: GrS, J1966 and J1976.
L56	pF-appending point	Lowest: C2011 and C1993. Highest: GrS and J1895 The more clay, the lower the pF-app. point.
L58	C-inorganic	Ranges from 0.04 (GrNE) to 0.07 (Ar).

The amount of earthworms is by far the lowest in Ar (*Table 52*). Medium results were found for the sandy soils of GrS and J1895 and the highest values were found in the old *Corylus* parcels (J1993 and J1995).

Table 52 Earthworm sampling results (parcels missing in the table have not been sampled).

			Ar	C1993	GrS	J1895	C1995	Mean
Category	**Unit**	**Soil depth (cm)**	**C-loamy hydro**	**C-loamy hydro**	**J-sandy**	**J-sandy**	**C-loamy brown**	
Earthworms	kg ha^{-1}	0-30	160	1300	613	467	1960	900 ± 324
Earthworms	kg ha^{-1}	30-60	0	80	80	200	67	85 ± 32

Compost

We chose to use the values for organic matter (OM) content of CDM (2017) instead of Attero (2017) or DLO (2011). The applied compost in the orchard is relatively old, compared to compost from compost companies. Therefore, we expect the OM-content to be relatively high, which matches best with the values of CDM (2017).

Manure

For manure we also choose to use the C-content values of CDM (2017), because we used that source for the compost too. Besides, the remaining added C after 1 year coincidentally turned out to be the same amount as calculations based on the numbers of DLO (2011).

Wood

The harvested wood volume of C1993 was based on C1995. Details about the number of trees, mean diameter and tree height can be found in Table 53.

Table 53 Tree species, diameter, height and number per hectare.

Parcel		**C2011**	**C1993**	**J1895**	**J1976**	**J1966**	**C1995**
Category	**Unit**	C-loamy hydro	C-loamy hydro	J-sandy	J-loamy	J-loamy	C-loamy brown
Species		*Corylus avellana*	*Corylus avellana*	*Juglans regia*	*Juglans regia*	*Juglans regia*	*Corylus avellana*
Number	# ha^{-1}	563	177	70	100	100	228
Mean diameter	cm (SE)	6.7 ± 0.2	22.7 ± 1.0	70 ± n=1	42 ± n=1	32 ± n=1	23.3 ± 0.4
Mean height	m (SE)	2.53 ± 0.14	6.81 ± 0.14	15.25 ± 0.32	12.25 ± 0.25	11.75 ± 0.75	7.87 ± 0.19

Corylus leaves

The chemical analysis of the leaves shows no remarkable results. The amount of P in the leaves is slightly higher than average. K, Ca, S, Fe, Mn, Zn and Cu-amounts are all normal and N, Mg and B-amounts are slightly lower than normal.

All results for harvested wood and fruits, manure application etc. were based on the orchard as a whole, so these results are not parcel specific and are reallocated to the parcels.

Appendix C.5 Results: Raw data

Table 54 Raw data

Data code	Data type	Parameter	Comment	Unit	Depth	Ar	Ar
		Chronosequence				C-loamy hydro	C-loamy hydro
		Sample weight				0.50	0.50
D1	Vegetation description	Main vegetation				Mais	Mais
D2	Soil description	Soil description					
L01	Soil lab	Soil sample report name				A1	A2
L02	Soil lab	Soil sample report #				743893/ 650734	768637
L03	Soil lab	Soil sample code (map)				A1	A2
L04	Soil lab	Soil sample date				14-2-2019	24-4-2019
L05	Soil lab	C-organic (SOC)		% (mass)	0-30	1.4	1.4
L06	Soil lab	C-organic (SOC)		% (mass)	30-60	0.5	
L07	Soil lab	SOM		% (mass)	0-30	3.1	3.00
L08	Soil lab	SOM		% (mass)	30-60	2.6	
L09	Soil lab	C/SOM	ratio		0-30	0.45	0.47
L10	Soil lab	C/SOM	ratio		30-60	0.19	
L11	Soil lab	N	stock	kg N/ha	0-30	5040	5380
L12	Soil lab	C/N	ratio		0-30	12	10
L13	Soil lab	N	delivery capac	kg N/ha	0-30	80	100
L14	Soil lab	Nitrogen	available		0-30		
L15	Soil lab	S	available	kg S/ha	0-30	8	24
L16	Soil lab	S	stock	kg S/ha	0-30	985	905
L17	Soil lab	C/S	rate	rate	0-30	60	62
L18	Soil lab	S	delivery capac	kg S/ha	0-30	16	14
L19	Soil lab	Phosphate	available	mg P_2O_5/100g	0-30		
L20	Soil lab	P	available	kg P/ha	0-30	5.3	4.1
L21	Soil lab	P (Phosphorus)	stock	kg P/ha	0-30	590	590
L22	Soil lab	K	available	kg K/ha	0-30	260	420
L23	Soil lab	K	stock	kg K/ha	0-30	495	450
L24	Soil lab	K (Potasium)	available	mg K_2O/100g	0-30		
L25	Soil lab	K (Potasium)	stock	?	0-30		
L26	Soil lab	Ca	available	kg Ca/ha	0-30	100	200
L27	Soil lab	Ca	stock	kg Ca/ha	0-30	4105	2635
L28	Soil lab	Mg	available	kg Mg/ha	0-30	330	325
L29	Soil lab	Mg	stock	kg Mg/ha	0-30	435	400
L30	Soil lab	Magnesium	available		0-30		
L31	Soil lab	Na	available	kg Na/ha	0-30	30	40
L32	Soil lab	Na	stock	kg Na/ha	0-30	40	40
L33	Soil lab	pH	until 2000 -KCl	pH	0-30	5.3	4.9
L34	Soil lab	Carbonic acid lime		%	0-30	<0,2	<0,2
L35	Soil lab	Clay		%	0-30	8	8
L36	Soil lab	Silt		%	0-30	21	13
L37	Soil lab	Sand		%	0-30	68	76
L38	Soil lab	Clay-humus		mmol+/kg	0-30	66	51
L39	Soil lab	CEC	occupation	%	0-30	94	85
L40	Soil lab	Ca	occupation	%	0-30	76	63
L41	Soil lab	Mg	occupation	%	0-30	13	16
L42	Soil lab	K	occupation	%	0-30	4.7	5.5
L43	Soil lab	Na	occupation	%	0-30	0.6	0.8
L44	Soil lab	H	occupation	%	0-30	0.2	0.2
L45	Soil lab	Al	occupation	%	0-30	<0,1	0.2
L46	Soil lab	Crumble capacity	grade		0-30	9.1	9.1
L47	Soil lab	Soil crusting (verslemping)	grade		0-30	5.2	5.2
L48	Soil lab	Moisture retaining capacity		mm	0-30	60	56
L49	Soil lab	Micro-biol.-activity		mg N/kg	0-30	33	17
L50	Soil lab	Soil respiration (biol. Act.)		N/?	0-30		
L51	Soil lab	SOM annual breakdown		%	0-30	1.8	1.8
L52	Soil lab	SOM quality	grade		0-30	——	—
L53	Soil lab	Soil structure (Structuurdriehc	grade			goed	n zeer matig
L54	Soil lab	Texture (textuurdriehoek)	grade			grens lemig zand en zavel	and en zavel)
L55	Soil lab	Water retention curve		mm		60	56
L56	Soil lab	pF-appending point	moisture	%		12.3	10.4
L57	Soil lab	OM		kg/ha	0-30	126985	123315
L58	Soil lab	C-inorganic		%	0-30	0.07	0.07
M1	Soil flux	Manure application	flux	m3/yr (bovine slurry)			
M2	Soil flux	N-application	flux	kg /ha/ yr			
M3	Soil flux	Lime application	flux	Mg /ha/ yr			
M4	Soil flux	Compost application	flux	kg /ha/ yr			
M5	Soil flux	Manure application	flux	Mg /ha/ yr			
M6	Soil flux	Manure application (after 1 ye	flux	Mg /ha/ yr			
N01	Tree inventory	# Stems in plot	stock	#			
N02	Tree inventory	Mean Ø incl. border trees	stock	cm			
N03	Tree inventory	Mean Height (H)	stock	m			
N04	Tree inventory	Crown Ø	stock	m			
N05	Tree inventory	Crown (pruned away)		%			
N06	Tree inventory	Tree age (since planting orchard)		year			
V01	Vegetation flux	Thinning 2006 (50%)	flux	kg fresh/ ha			
V02	Vegetation flux	Thinning 2013 (50%)	flux	kg fresh/ ha			
V03	Vegetation flux	Thinning 2014 (63%)	flux	kg fresh/ ha			
V04	Vegetation flux	Prunings (50% composted)	flux	kg fresh/ ha/ yr			
V05	Vegetation flux	Grass/maize (dry matter)	flux	Mg DM/ ha/ yr			
V06	Vegetation flux	Fruits (harvest)	flux	kg dried and cleaned/ ha/ yr			
V07	Vegetation flux	Fruit shells to compost	flux	kg DM/ ha/ yr			
V08	Vegetation flux	Fruits decried	flux	kg DM/ ha/ yr			
V09	Vegetation flux	Fruit husks, leaves etc.	flux	kg DM/ ha/ yr			
V10	Vegetation flux	Fruits (harvest+decried)	flux	Mg C/ha/yr			
V11	Vegetation flux	Grass/maize (50% composted)	flux	Mg C/ha/yr			
V12	Vegetation flux	Fruits to compost	flux	Mg C/ha/yr			
W1	Soil inventory	Earthworm sample	stock	kg/ha	0-30	no	no
W2	Soil inventory	Earthworm sample	stock	kg/ha	30-60		
X1	Soil calculation	Area		m2			
X2	Soil calculation	Soil mass	stock	kg/30 cm/ha	gen.	4096290	4110500
X3	Soil calculation	Soil bulk density	stock	g/L	0-30	1365	1370
X4	Soil calculation	SOC	stock	kg/ha	0-30	53222	53222
X5	Soil calculation	SOC	stock	kg/ha	30-60	19008	0
X6	Soil calculation	SOC	stock	kg/ha	0-60		
X7	Soil calculation	C/P	rate	rate	0-30		
X8	Soil calculation	C-inorganic/C-organic	rate	rate			
Y01	Tree calculation	Number of trees	t=26 resp. 24	#/ha			
Y02	Tree calculation	Living wood	t=13/t=11	kg fresh biomass/ha			
Y03	Tree calculation	Living wood	t=21/t=18	kg fresh biomass/ha			
Y04	Tree calculation	Living wood	t=26/t=24	kg fresh biomass/ha			
Y05	Tree calculation	Sum of removed wood	t=26/t=24	kg fresh biomass/ha			
Y06	Tree calculation	Annual wood increement	t=0-13	kg fresh biomass/ha			
Y07	Tree calculation	Annual wood increement	t=13-21/t=11-1	kg fresh biomass/ha			
Y08	Tree calculation	Annual wood increement	t=21-26/t=19-2	kg fresh biomass/ha			
Y09	Tree calculation	1 Foliage	stock	kg fresh biomass/ha			
Y10	Tree calculation	2 Branches	stock	kg fresh biomass/ha			
Y11	Tree calculation	3 Stems	stock	kg fresh biomass/ha			
Y12	Tree calculation	4 AGB trees	stock	kg fresh biomass/ha			
Y13	Vegetation calculation	5 Herbs & grasses	stock	kg fresh biomass/ha			
Y14	Vegetation calculation	6 Roots herbs & grasses	stock	kg fresh biomass/ha			
Y15	Tree calculation	7 Fine roots trees	stock	kg fresh biomass/ha			
Y16	Tree calculation	8 Coarse roots trees	stock	kg fresh biomass/ha			
Y17	Tree calculation	9 current AGB (present at site)	stock	kg fresh biomass/ha			
Y18	Tree calculation	10 Branches and trees removed in total life tree	time stock	kg fresh biomass/ha			
Y19	Tree calculation	11 AGB-production	time stock	kg fresh biomass/ha			
Y20	Tree calculation	12 BGB	stock	kg fresh biomass/ha			
Y21	Tree calculation	13 TB (current AGB+BGB)	stock	kg fresh biomass/ha			
Y22	Tree calculation	1 Foliage	stock	kg dry biomass/ha			
Y23	Tree calculation	2 Branches	stock	kg dry biomass/ha			
Y24	Tree calculation	3 Stems	stock	kg dry biomass/ha			
Y25	Tree calculation	4 current AGB trees	stock	kg dry biomass/ha			
Y26	Vegetation calculation	5 Herbs & grasses	stock	kg dry biomass/ha			
Y27	Vegetation calculation	6 Roots herbs & grasses	stock	kg dry biomass/ha			
Y28	Tree calculation	7 Fine roots trees	stock	kg dry biomass/ha			
Y29	Tree calculation	8 Coarse roots trees	stock	kg dry biomass/ha			
Y30	Vegetation calculation	9 current AGB	stock	kg dry biomass/ha			
Y31	Tree calculation	10 Branches and trees removed in total life tree	time stock	kg dry biomass/ha			
Y32	Tree calculation	11 AGB-production	time stock	kg dry biomass/ha			
Y33	Vegetation calculation	12 BGB	stock	kg dry biomass/ha			
Y34	Vegetation calculation	13 TB (current AGB+BGB)	stock	kg dry biomass/ha			
Y35	Tree calculation	1 Foliage	stock	kg C/ha			
Y36	Tree calculation	2 Branches	stock	kg C/ha			
Y37	Tree calculation	3 Stems	stock	kg C/ha			
Y38	Tree calculation	4 AGB trees (present)	stock	kg C/ha			
Y39	Vegetation calculation	5 Herbs & grasses	stock	kg C/ha			
Y40	Vegetation calculation	6 Roots herbs & grasses	stock	kg C/ha			
Y41	Tree calculation	7 Fine roots trees	stock	kg C/ha			
Y42	Tree calculation	8 Coarse roots trees	stock	kg C/ha			
Y43	Vegetation calculation	9 current AGB-tree+grass	stock	kg C/ha			
Y44	Tree calculation	10 Branches and trees removed in total life tree	time stock	kg C/ha			
Y45	Vegetation calculation	11 AGB-tree+grass (prod.)	time stock	kg C/ha			
Y46	Vegetation calculation	12 BGB	stock	kg C/ha			
Y47	Vegetation calculation	13 TB (current AGB+BGB)	stock	kg C/ha			
Y48	Tree calculation	14 AGB-Tree pres+removed	stock	kg C/ha			
Z01	Total calculation	Tot C-stock (SOC(0-60)+TBpres	stock	kg C/ha			
Z02	Total calculation	SOC increase/yr	flux	kg C/ha/yr	0-30		
Z03	Total calculation	SOC increase/yr	flux	kg C/ha/yr	30-60		
Z04	Total calculation	SOC increase/yr	flux	kg C/ha/yr	0-60		
Z05	Total calculation	BGB-grasses C increase/yr	flux	kg C/ha/yr			
Z06	Total calculation	BGB-trees C increase/yr	flux	kg C/ha/yr			
Z07	Total calculation	BGB-C increase/yr	flux	kg C/ha/yr			
Z08	Total calculation	AGB-all C increase	stock	kg C/ha			
Z09	Vegetation calculation	AGB-all C increase/yr (current)	flux	kg C/ha/yr			
Z10	Vegetation calculation	AGB-all C increase/yr (product	flux	kg C/ha/yr			
Z11	Total calculation	TB_C increase/yr (production)	flux	kg C/ha/yr			
Z12	Total calculation	Tot C-flux (increase/yr)	flux	kg C/ha/yr			
Z13	Total calculation	SOC increase %	flux	%			
Z14	Total calculation	SOC/Tot C					
Z15	Tree calculation	AGB-tree-prod	flux	Mg C/ha/yr			
Z16	Vegetation calculation	AGB-herbs_grass	flux	Mg C/ha/yr			
Z17	Tree calculation	Foliage & fruits	flux	Mg C/ha/yr			
ZZ	Soil lab	Soil lab result remarks					
ZZ2	HWC						
ZZ3	Bacteria aerobe						
ZZ4	Bacteria anaerobe						
ZZ5	Fungi, yeasts						